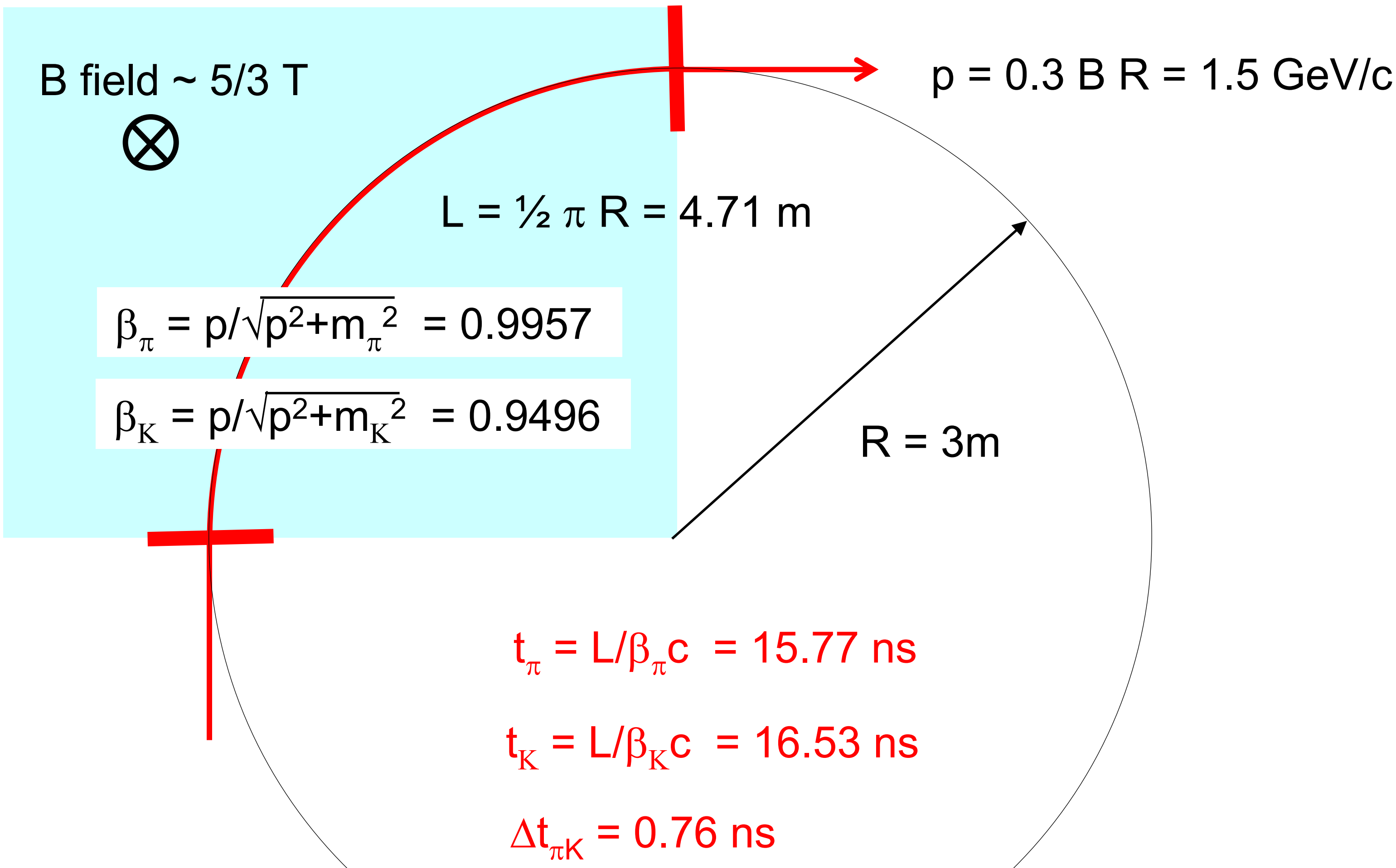
Scintillation Detectors

Introduction
Components
- Scintillator
- Light Guides
- Photomultiplier Tubes

Formalism/Electronics
Timing Resolution

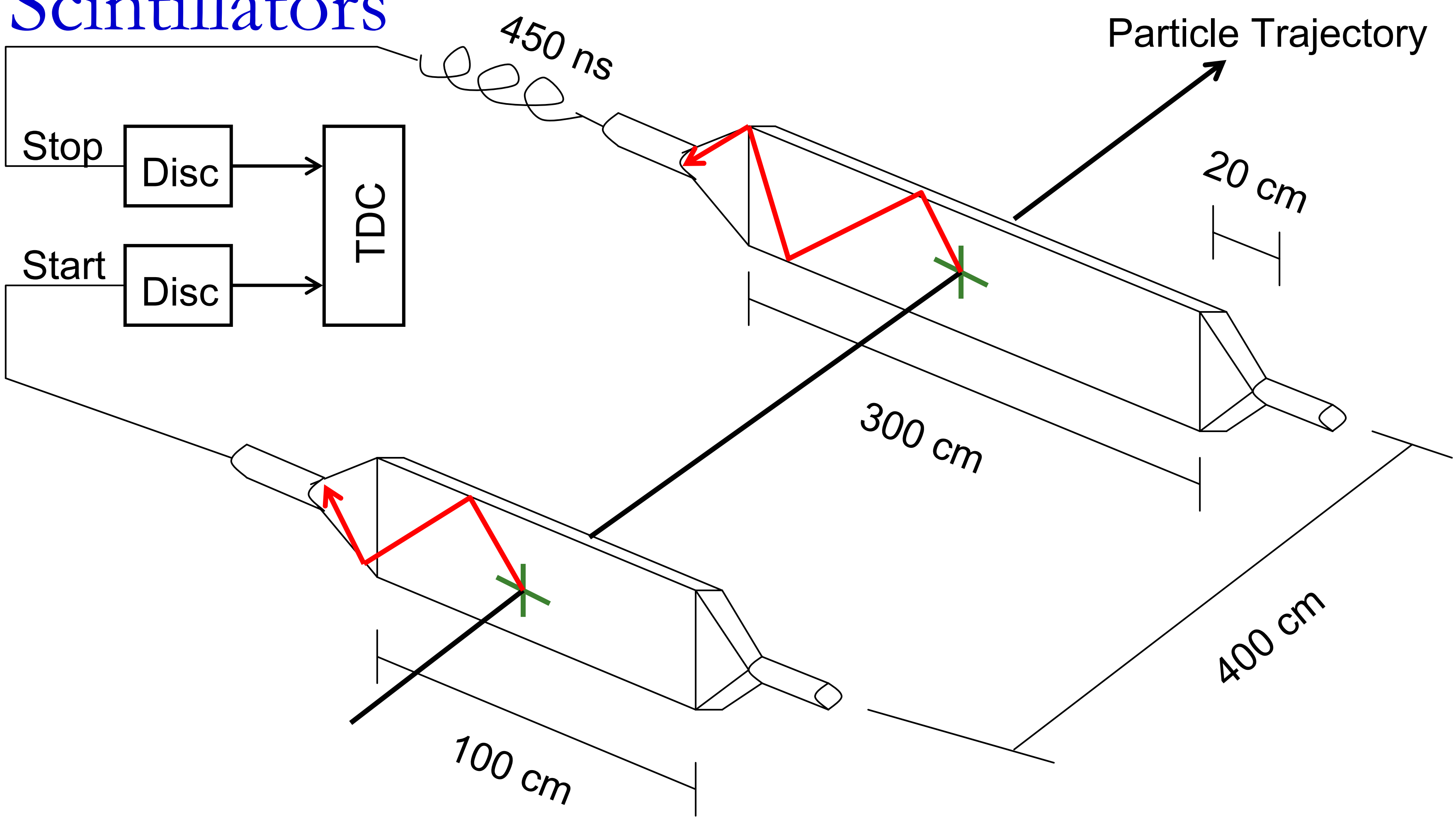
Elton Smith JLab 2006 Detector/Computer Summer Lecture Series

Experiment basics

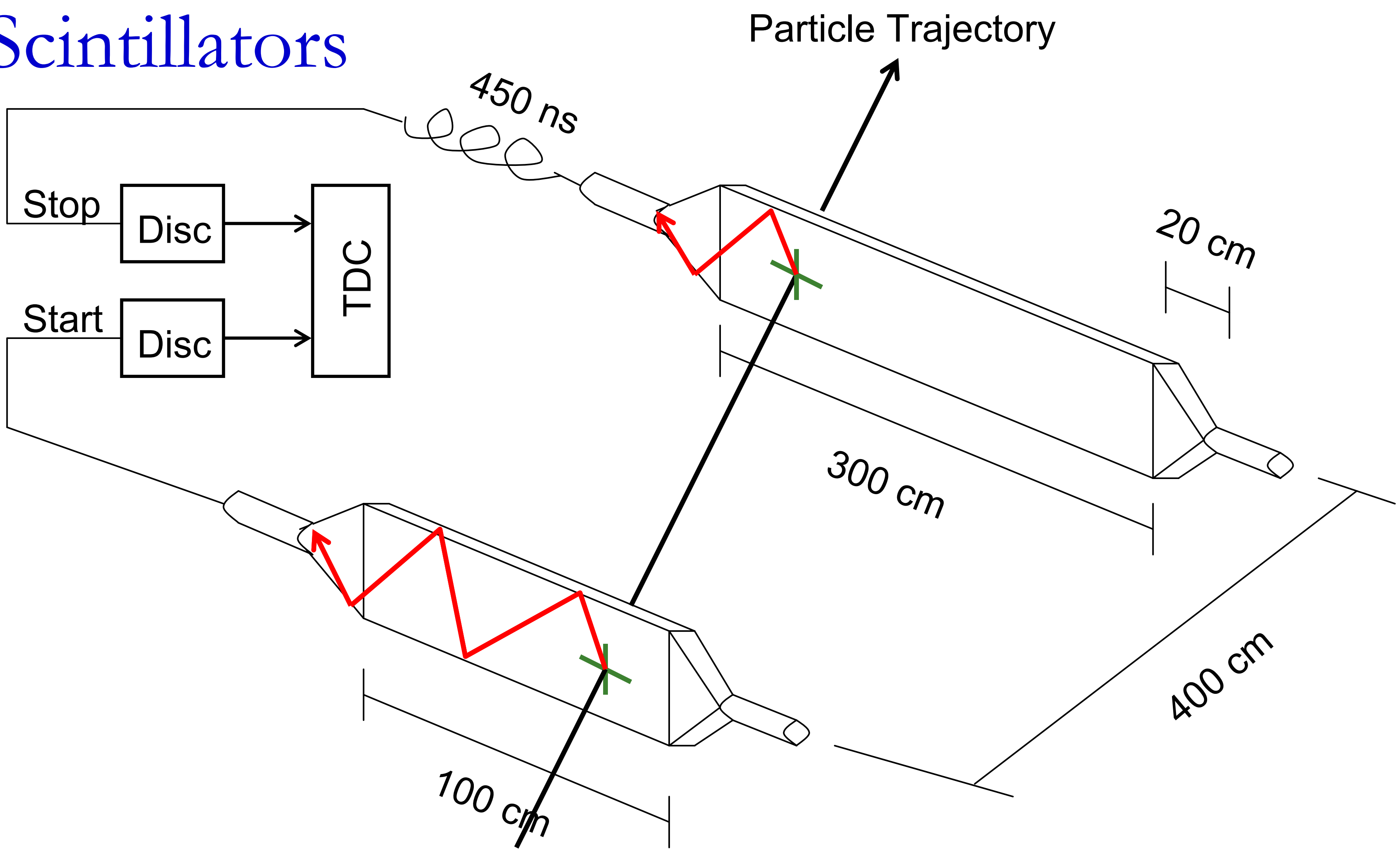


Particle Identification by time-of-flight (TOF) requires
Measurements with accuracies of ~ 0.1 ns

Measure the Flight Time between two Scintillators



Measure the Flight Time between two Scintillators



Propagation velocities

- $c = 30$ cm/ns
- $v_{scint} = c/n = 20$ cm/ns
- $v_{eff} = 16$ cm/ns
- $v_{pmt} = 0.6$ cm/ns
- $v_{cable} = 20$ cm/ns

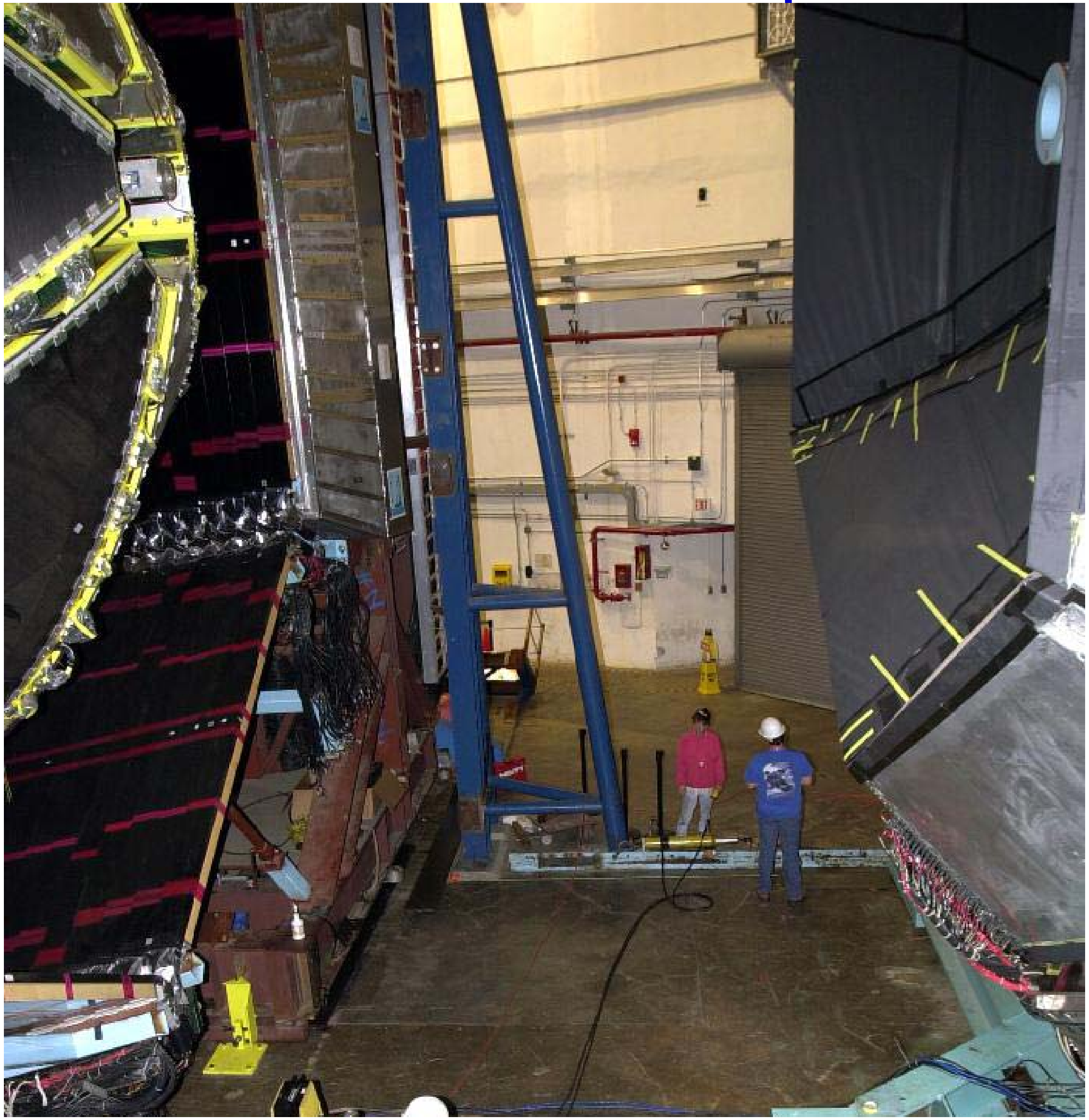
$\Delta t \sim 0.1$ ns

$\Delta x \sim 3$ cm

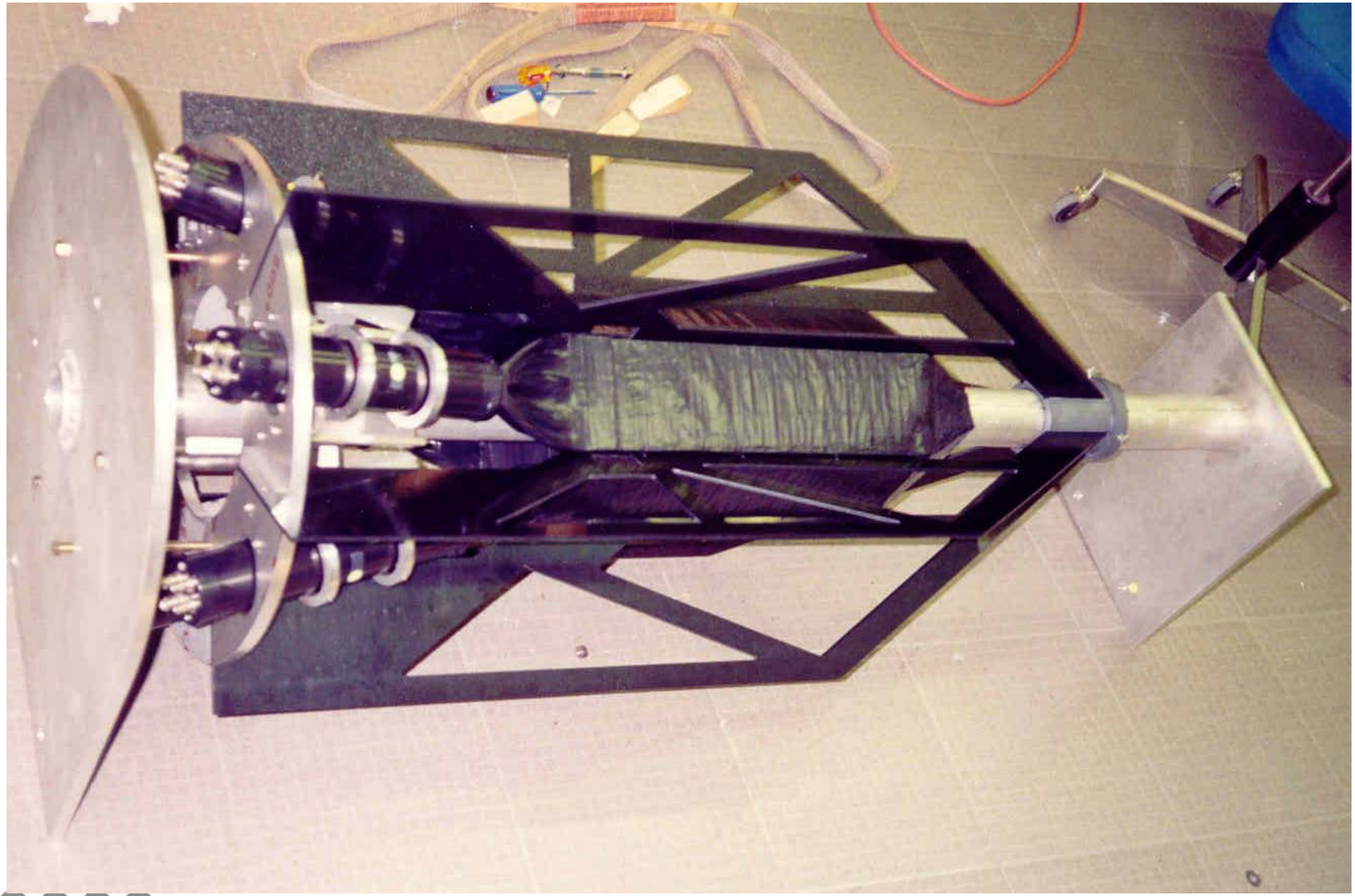
TOF scintillators stacked for shipment

CLAS detector open for repairs

CLAS detector with FC pulled apart



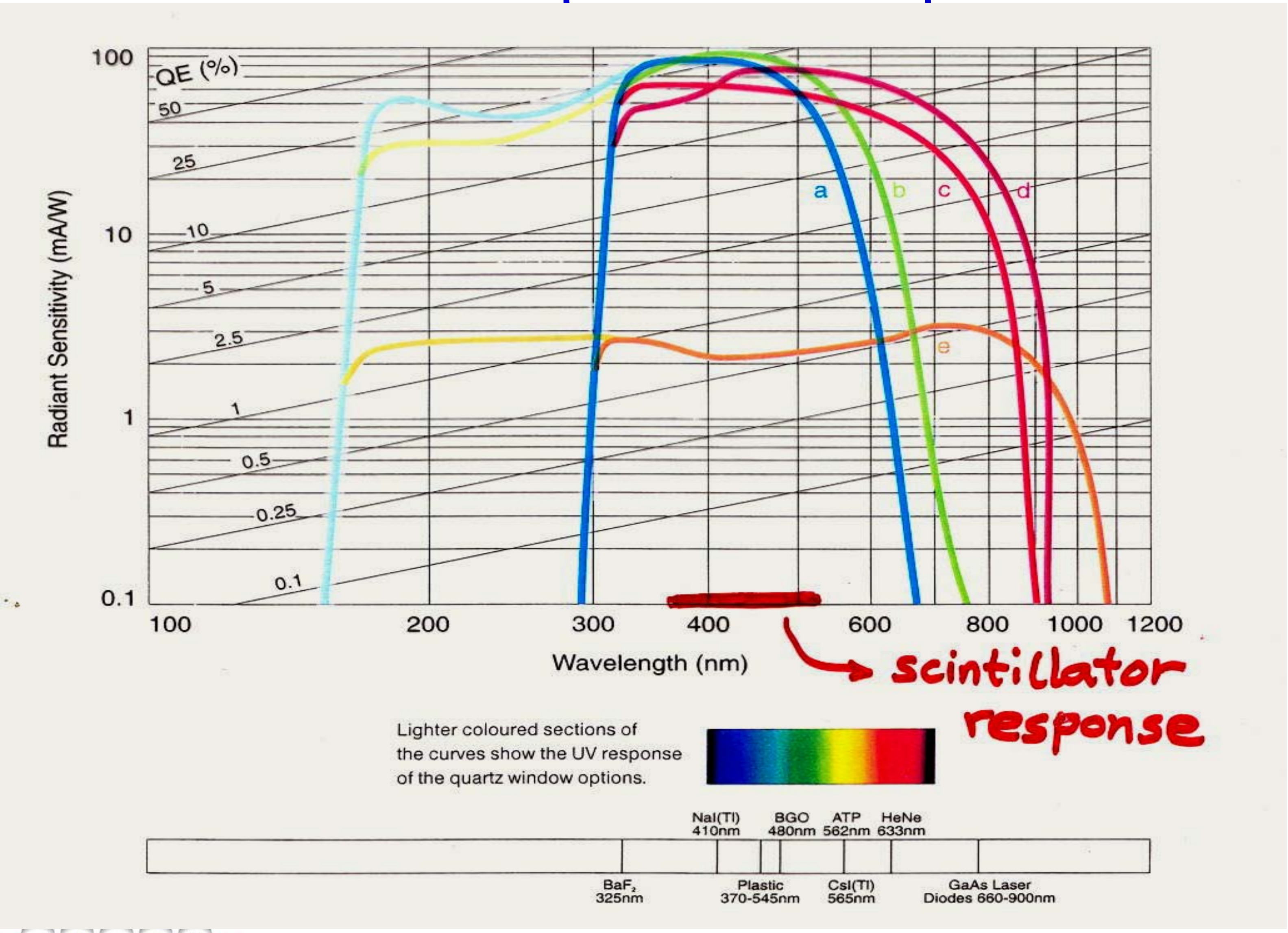
Start counter assembly



Scintillator types

- Organic
  - Liquid
    - Economical
    - messy
  - Solid
    - Fast decay time
    - long attenuation length
    - Emission spectra
- Inorganic
  - Anthracene
    - Unused standard
  - NaI, CsI
    - Excellent γ resolution
    - Slow decay time
  - BGO
    - High density, compact

Photocathode spectral response



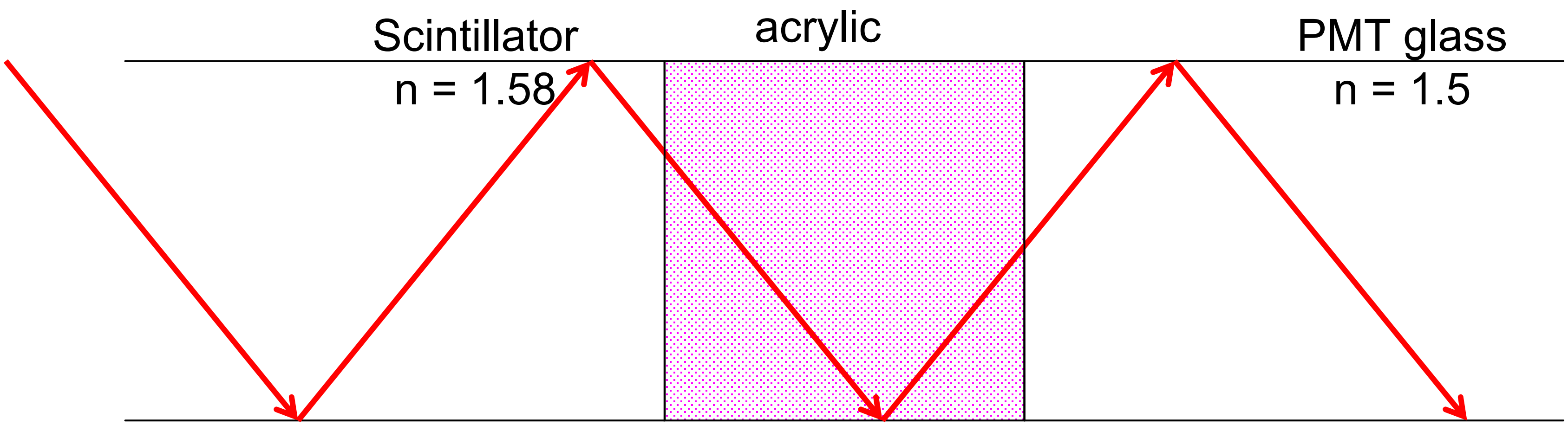
Scintillator thickness

- Minimizing material vs. signal/background
- CLAS TOF: 5 cm thick
  - Penetrating particles (e.g. pions) loose 10 MeV
- Start counter: 0.3 cm thick
  - Penetrating particles loose 0.6 MeV
  - Photons, e^+e^- backgrounds ~ 1MeV contribute substantially to count rate
- Thresholds may eliminate these in TOF

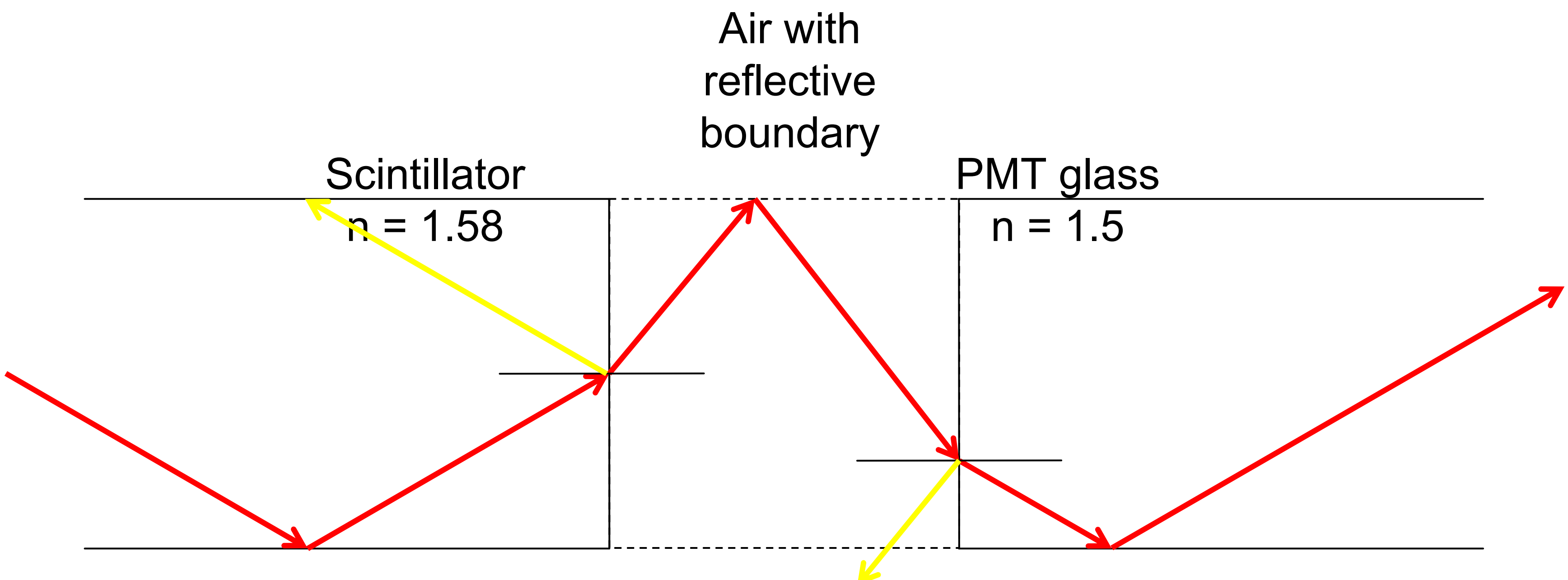
Light guides

- Goals
  - Match (rectangular) scintillator to (circular) pmt
  - Optimize light collection for applications
- Types
  - Plastic
  - Air
  - None
  - “Winston” shapes

Reflective/Refractive boundaries



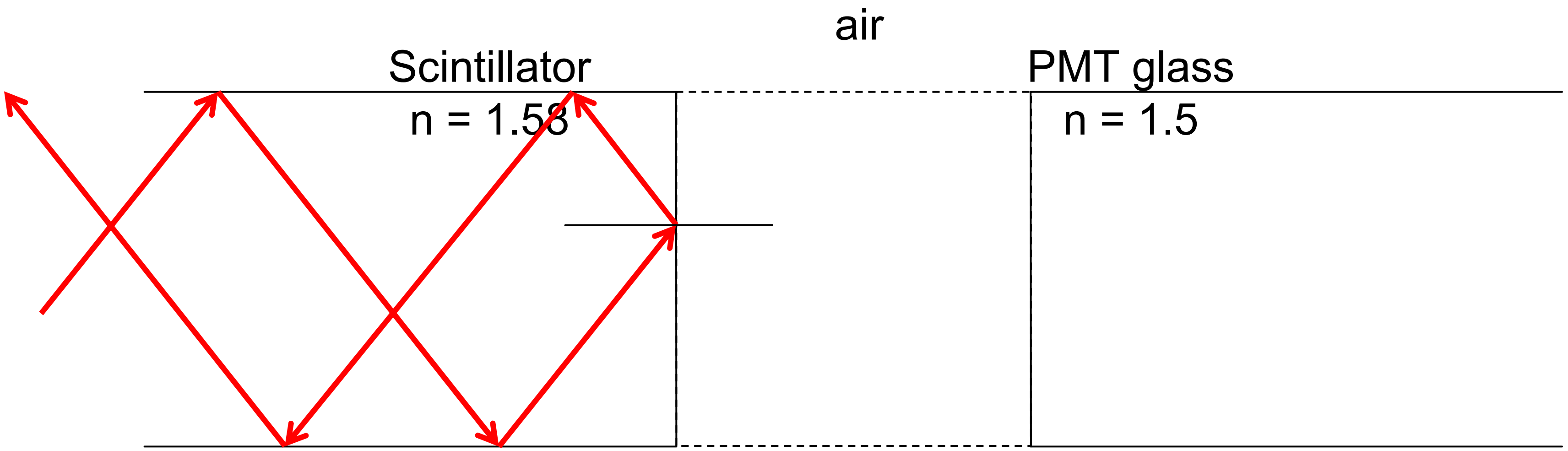
Reflective/Refractive boundaries



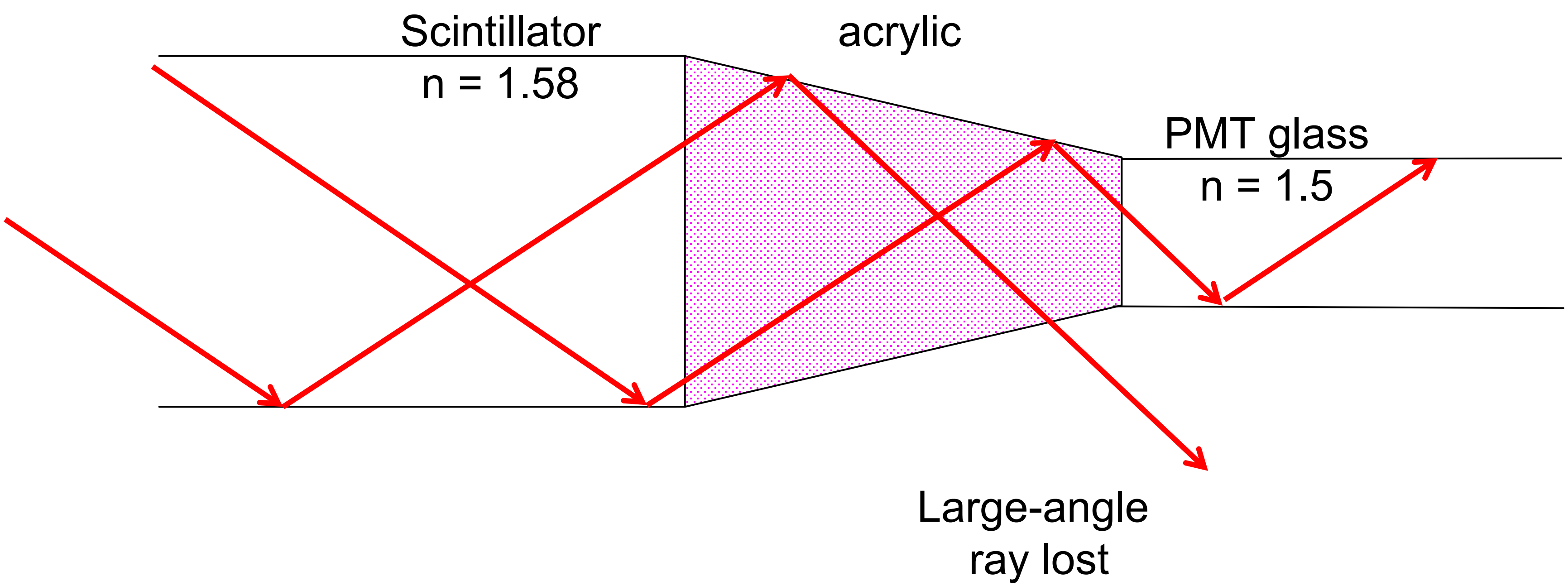
$$R_{air} = \left(\frac{1-n}{1+n} \right)^2 \approx 4-5\%$$

(reflectance at normal incidence)

Reflective/Refractive boundaries



Reflective/Refractive boundaries



Acceptance of incident rays at fixed angle depends on position at the exit face of the scintillator

Winston Cones - geometry

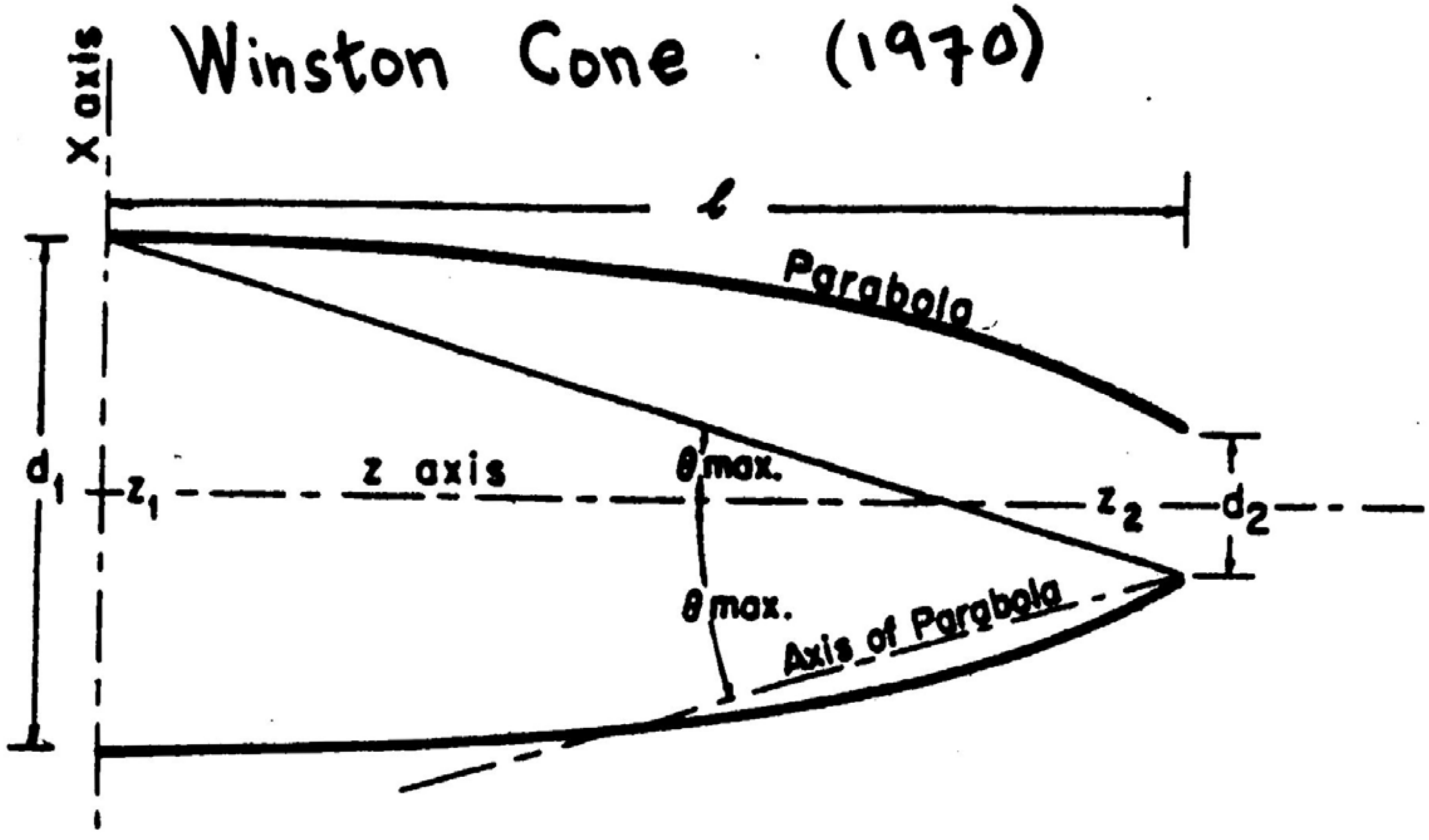


FIG. 2. Construction of an ideal light collector for the case of constant index of refraction. In this example, $\theta_{max} = 16°$.

Winston Cone - acceptance

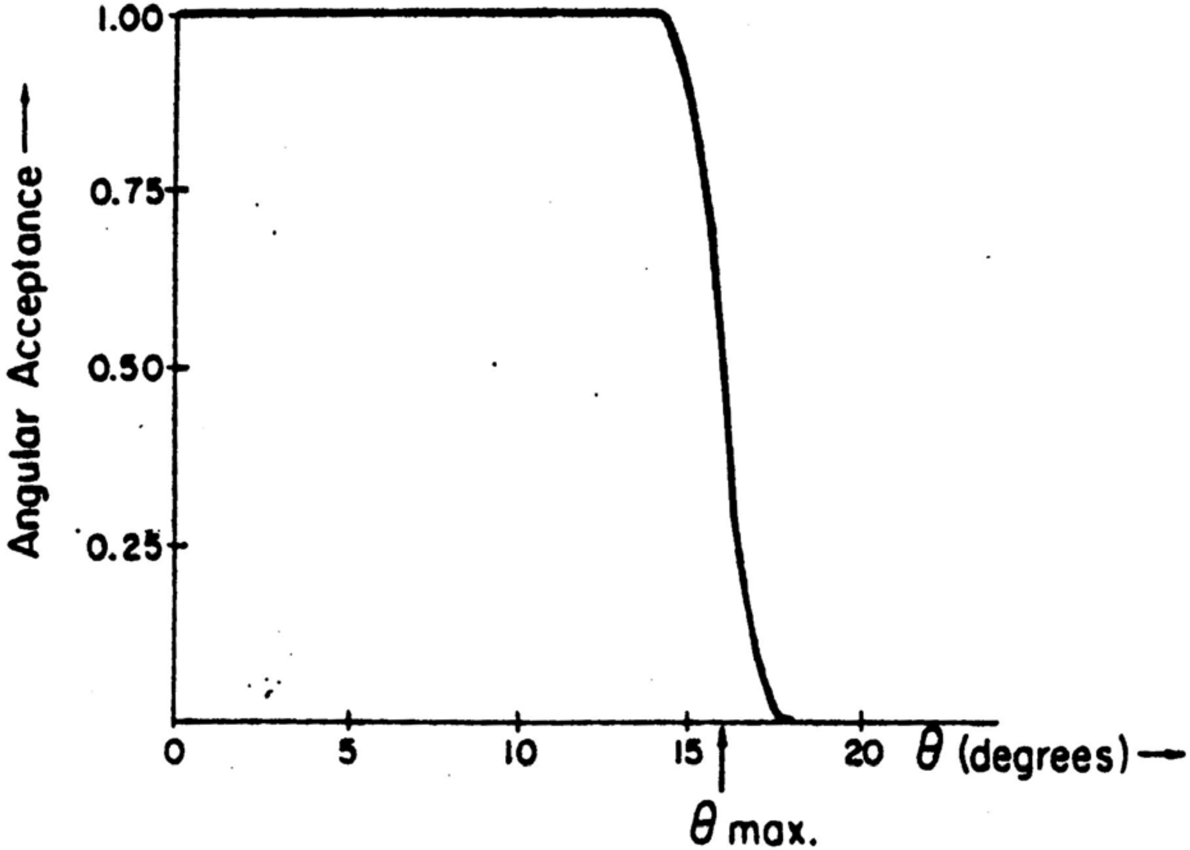
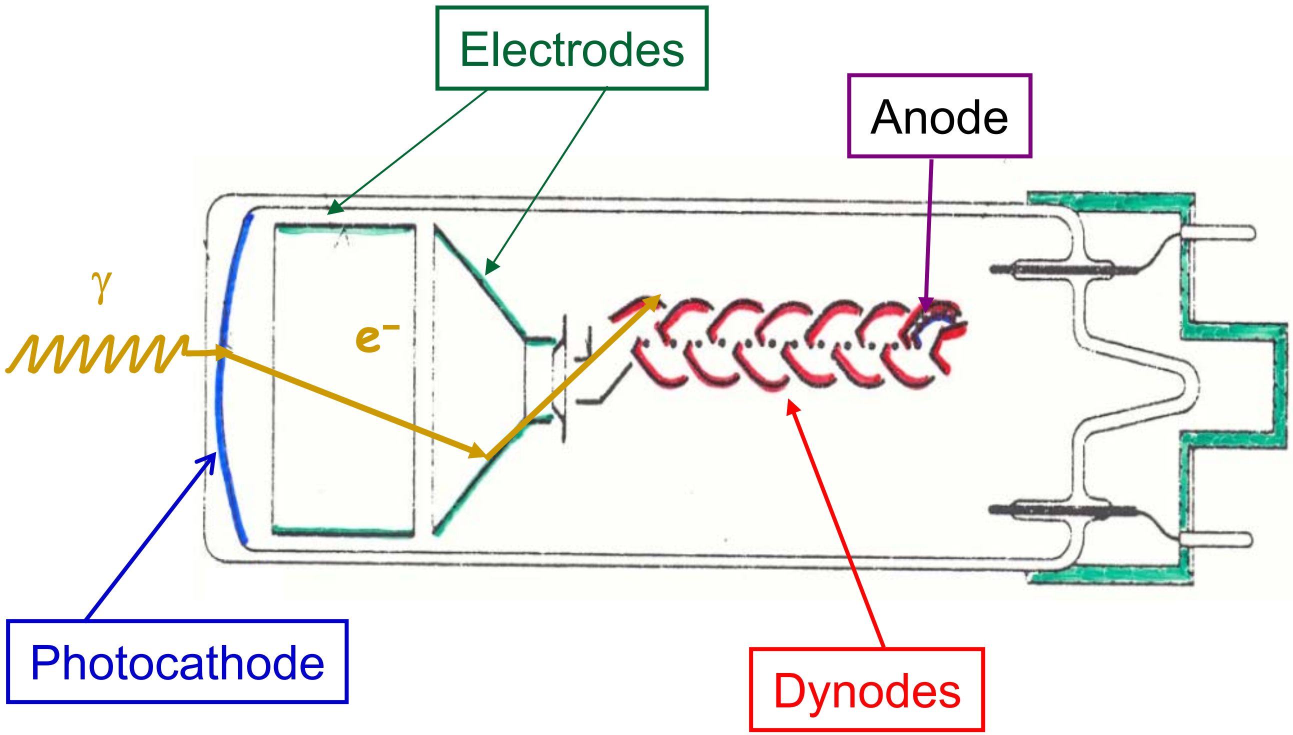


FIG. 4. The angular acceptance as a function of angle of incidence at the entrance aperture for an ideal three-dimensional light collector. Note that the angular acceptance cuts off over a region $\Delta\theta$ approximately 1° centered about θ_{max}. In this example, $\theta_{max} = 16°$.

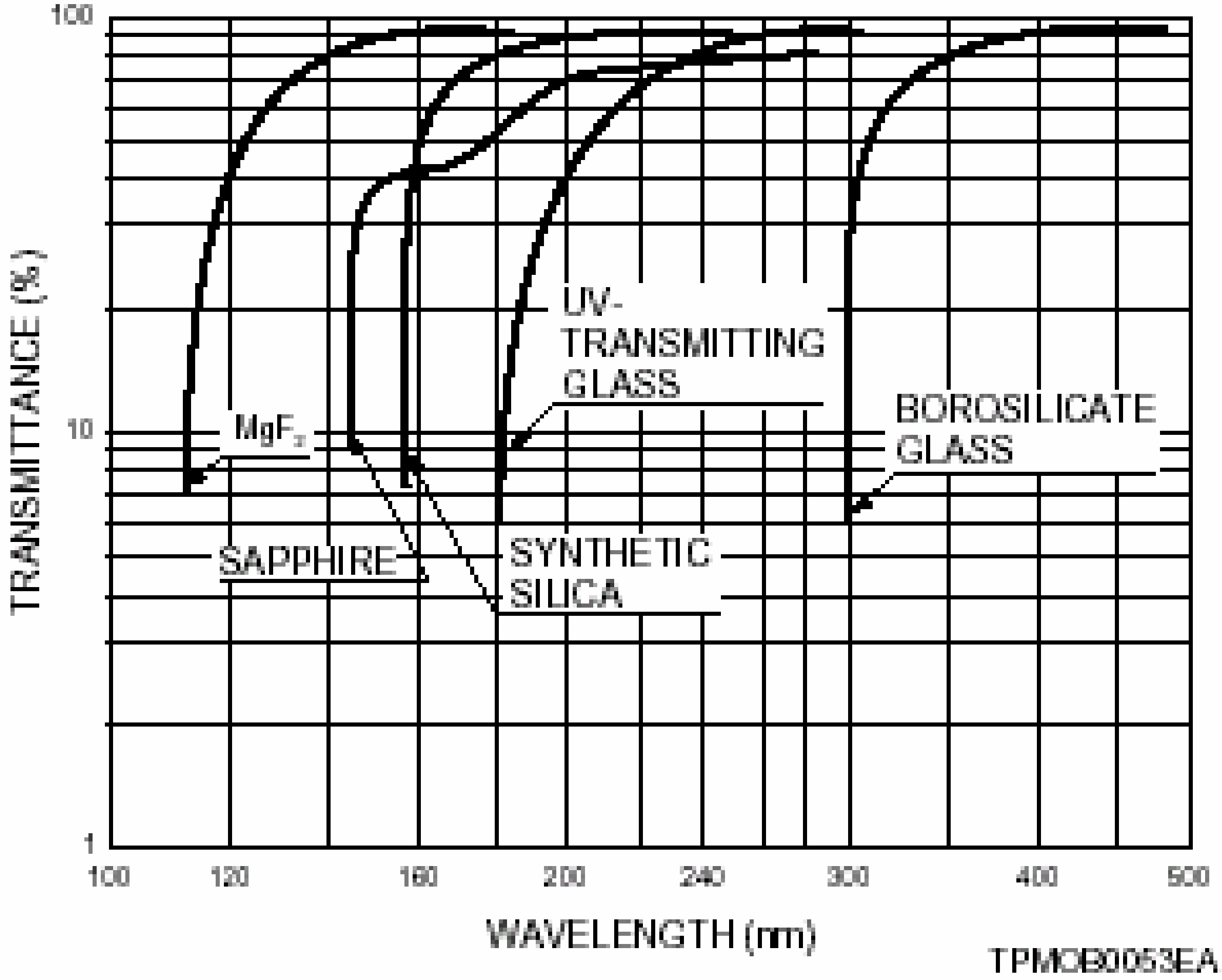
Photomultiplier tube, sensitive light meter

Gain ~ 10^6 - 10^7



56 AVP pmt

Window Transmittance

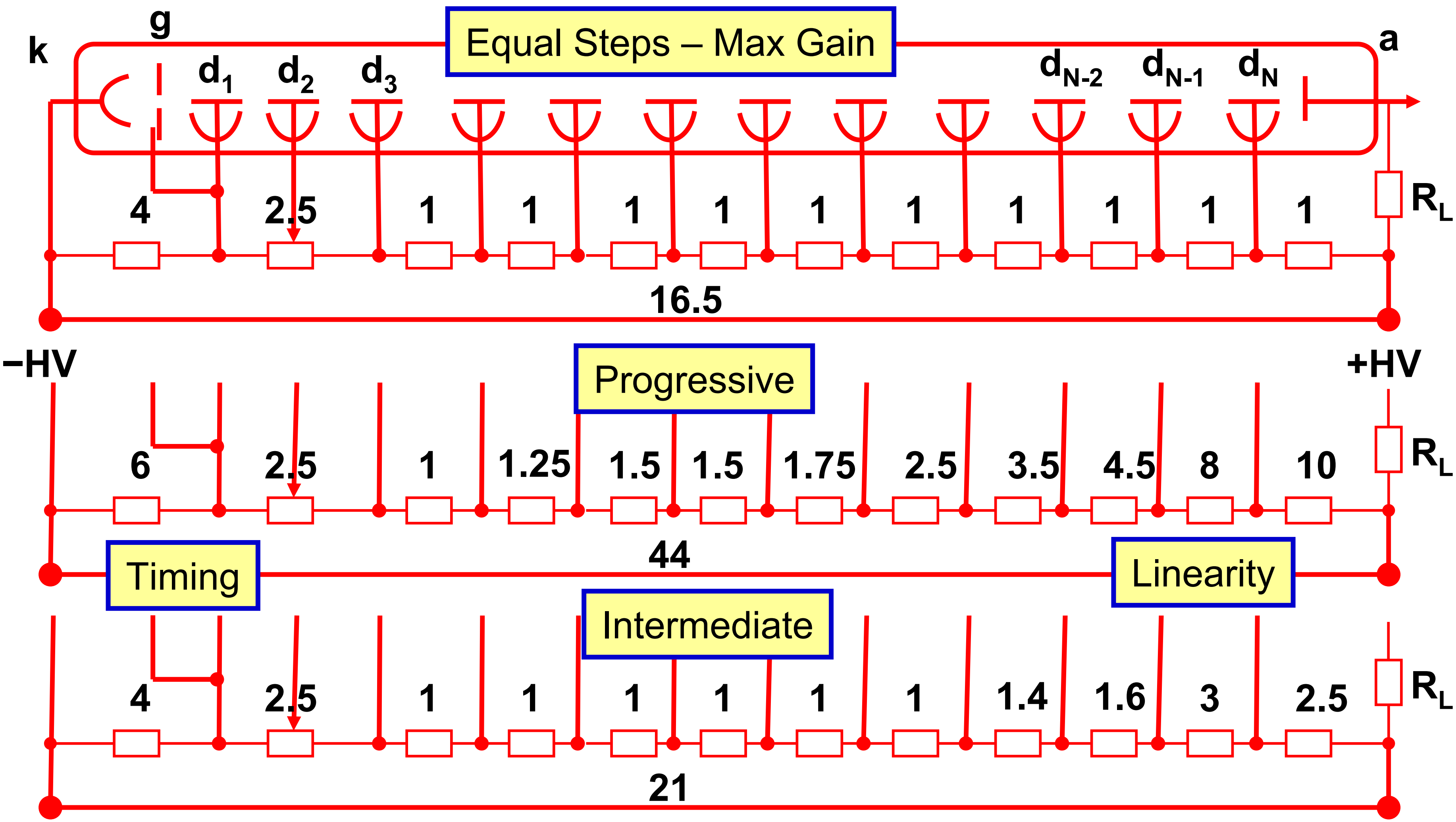


Voltage dividers

- Equal voltage steps
  - Maximum gain
- Progressive, higher voltage near anode
  - Excellent linearity, limited gain
- Time optimized, higher voltage at cathode
  - Good gain, fast response

- Zeners
  - Stabilize voltages independent of gain
- Decoupling capacitors
  - “reservoirs” of charge during pulsed operation

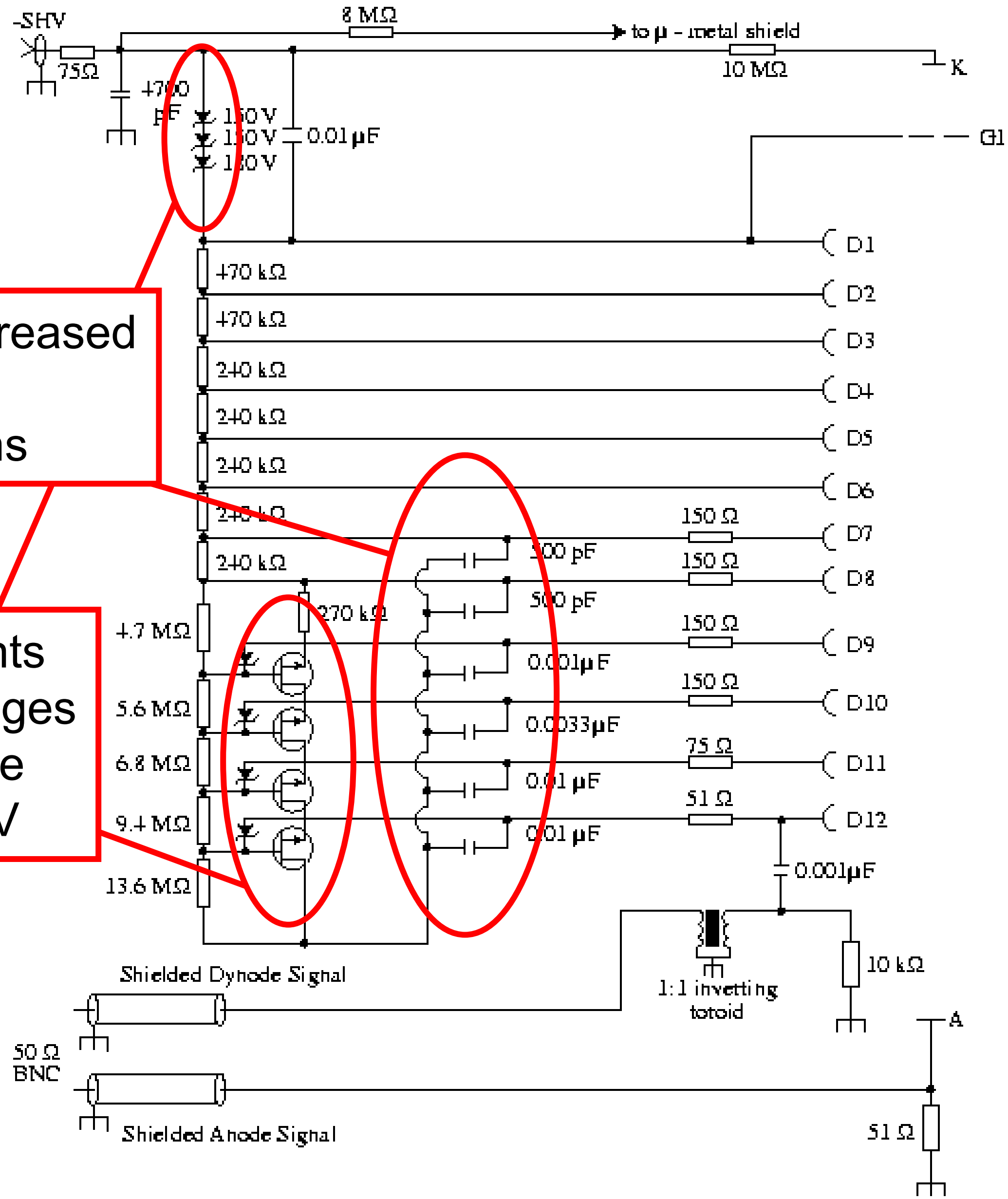
Voltage Dividers



Voltage Divider

Capacitors for increased linearity in pulsed applications

Active components to minimize changes to timing and rate capability with HV



High voltage

- Positive (cathode at ground)
  - low noise, capacitative coupling
- Negative
  - Anode at ground (no HV on signal)
- No (high) voltage
  - Cockcroft-Walton bases

Effect of magnetic field on pmt

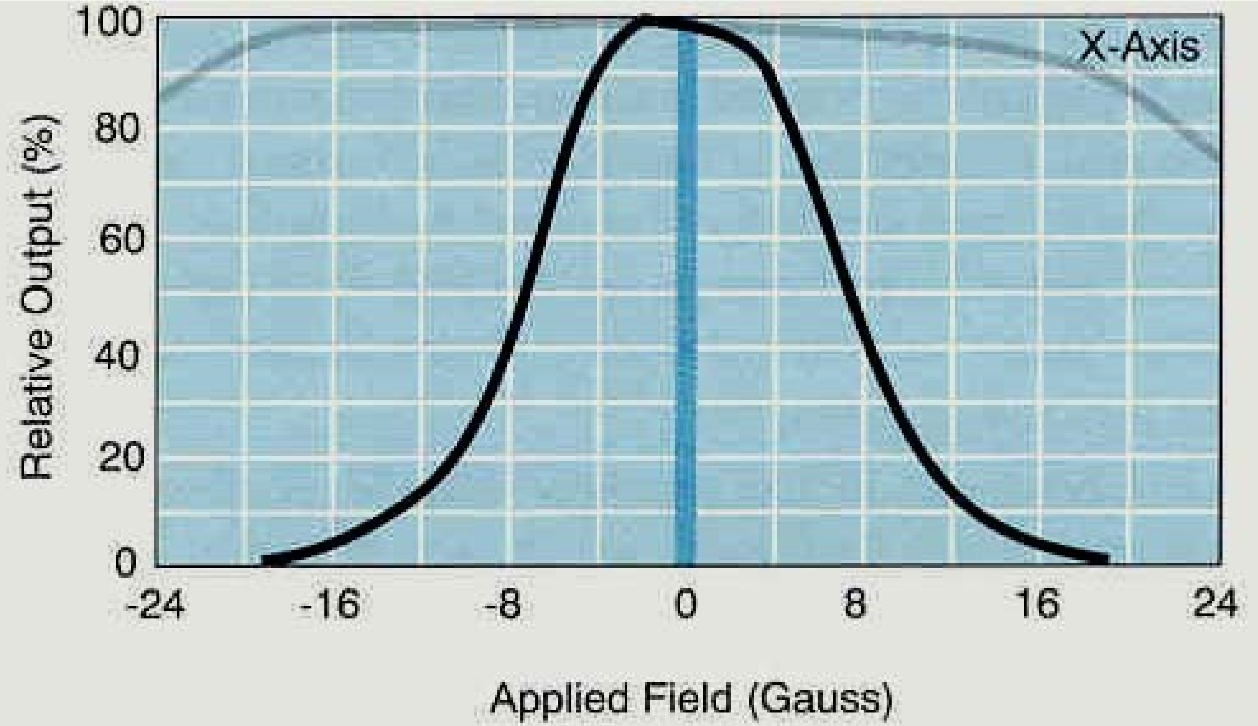
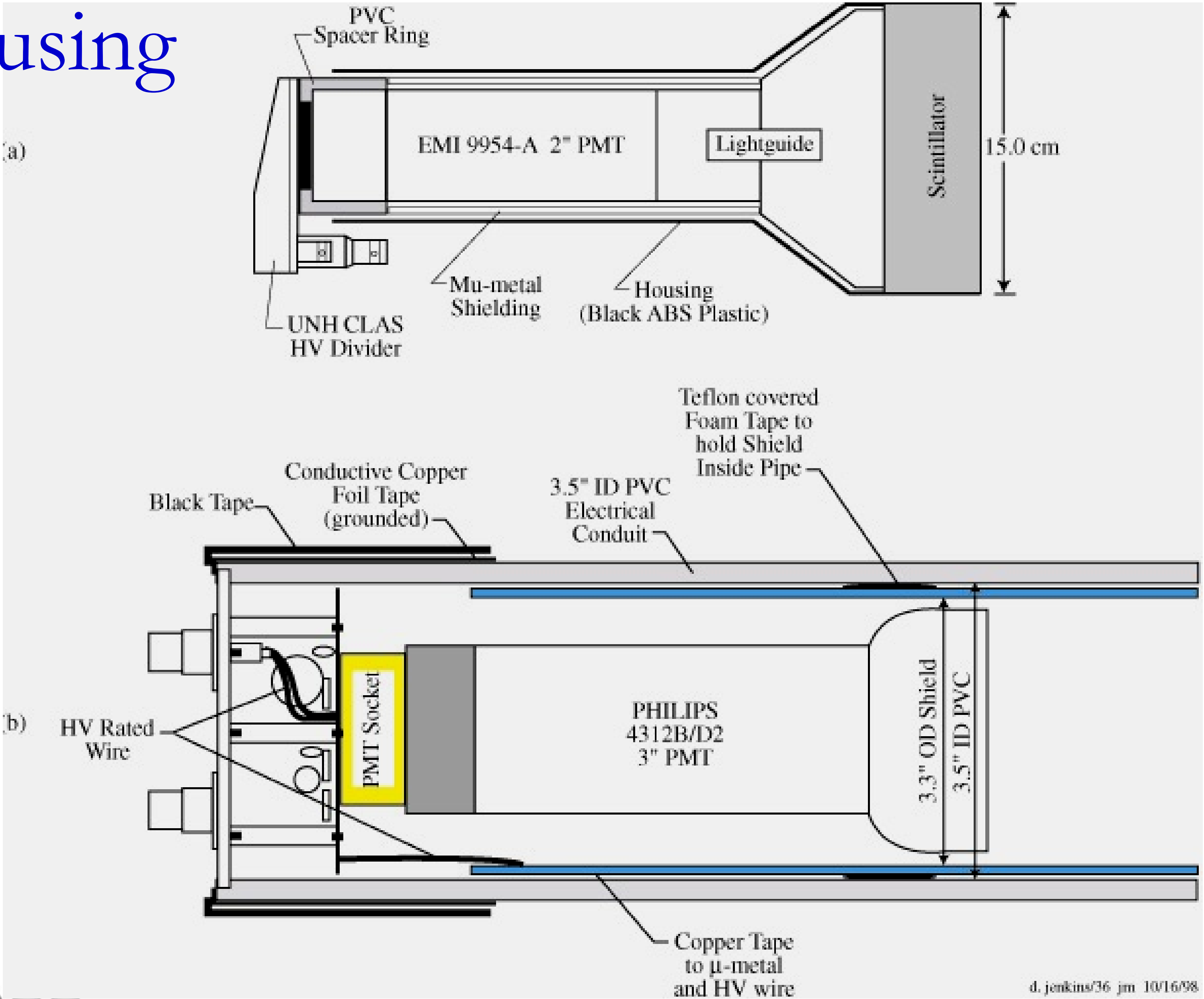


Figure 32

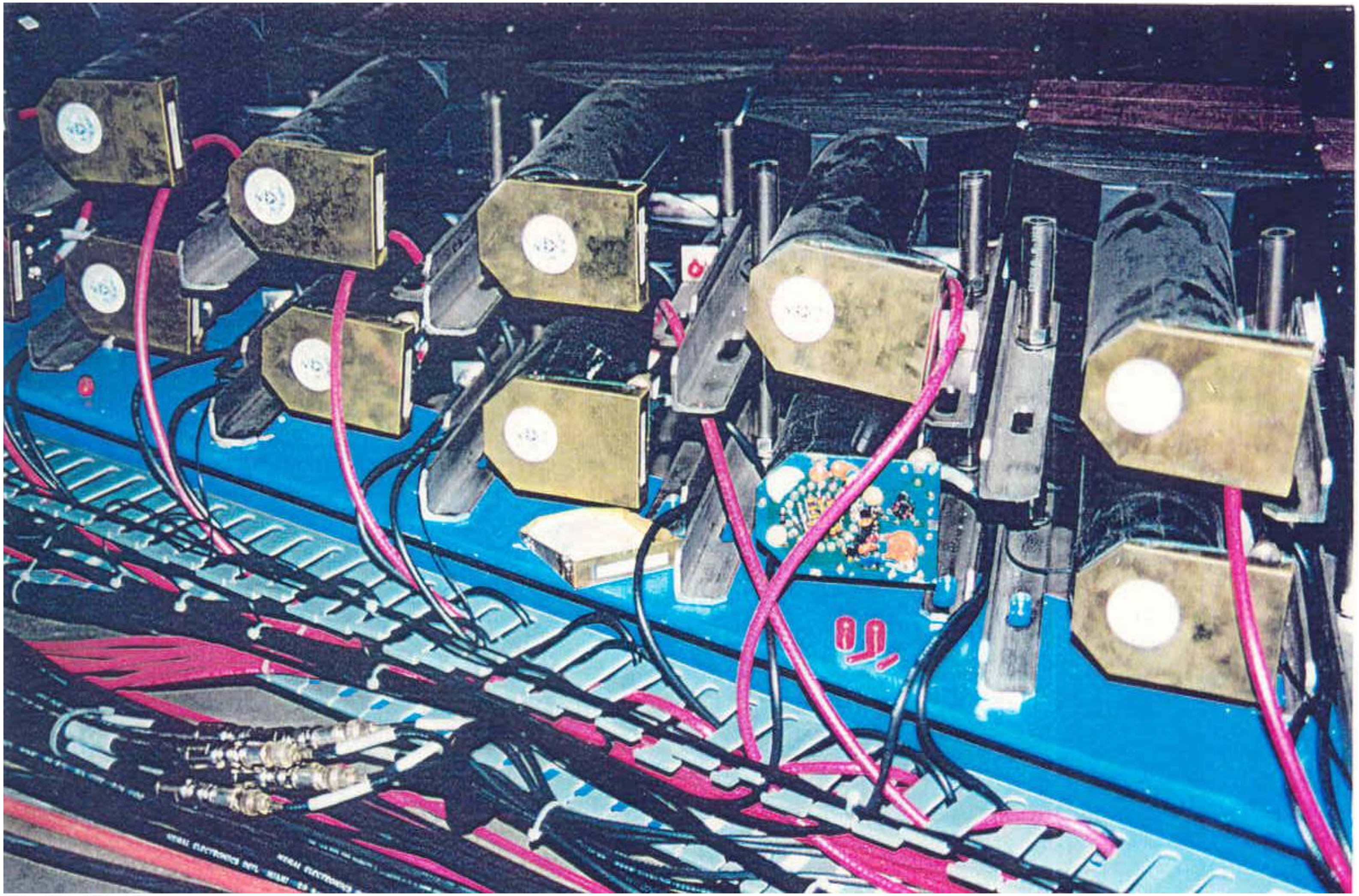
Demostrating how a wrapped mu-metal shield reduces the sensitivity of a 9106 photomultiplier to external magnetic fiels. Solid line: unshield; grey line: wrapped shield; shaded region: earth's field. Field aligned across the first dynode, X axis.

Housing

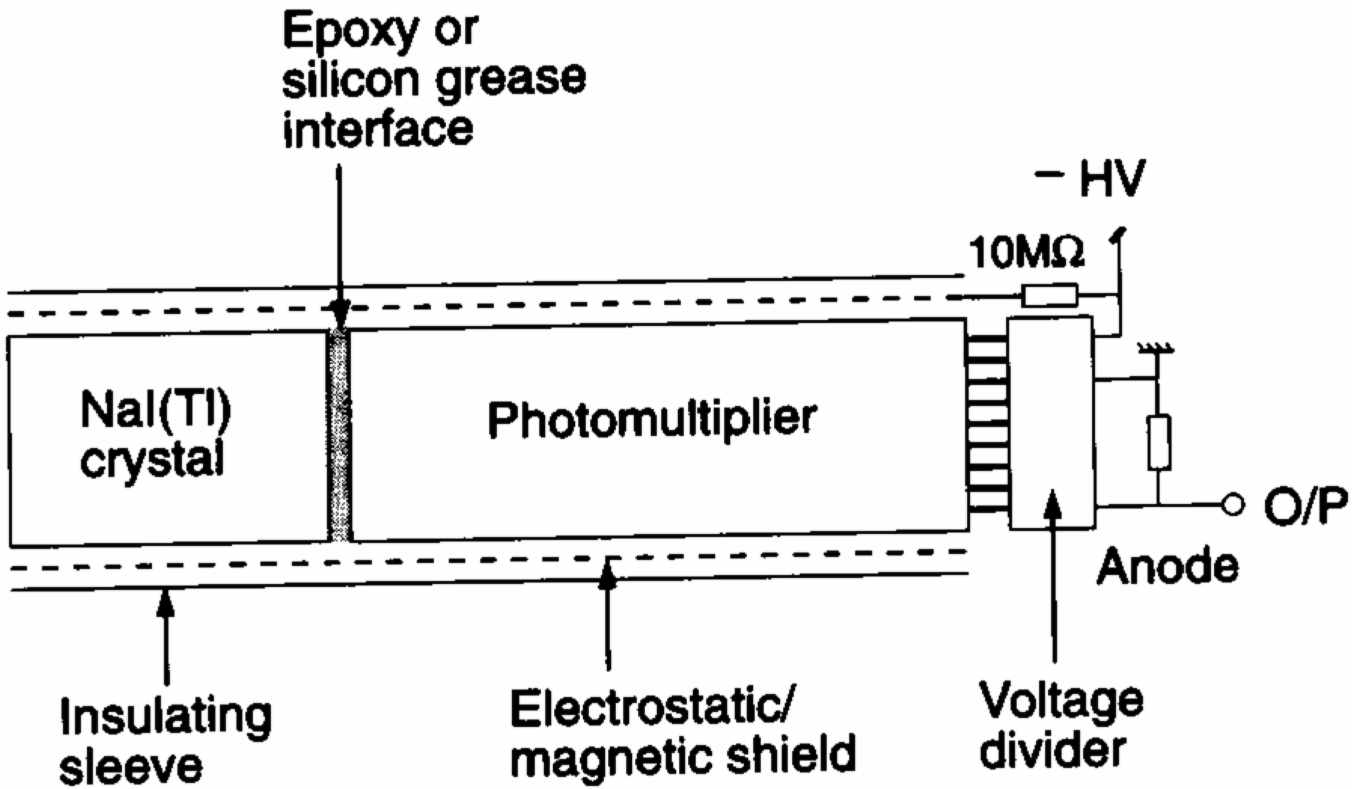


(a)
PVC Spacer Ring
EMI 9954-A 2" PMT
Lightguide
Scintillator
15.0 cm
Mu-metal Shielding
Housing (Black ABS Plastic)
UNH CLAS HV Divider
(b)
Teflon covered Foam Tape to hold Shield Inside Pipe
Conductive Copper Foil Tape (grounded)
Black Tape
3.5" ID PVC Electrical Conduit
HV Rated Wire
PMT Socket
PHILIPS 4312B/D2 3" PMT
3.3" OD Shield
3.5" ID PVC
Copper Tape to µ-metal and HV wire
d. jenkins/36 jm 10/16/98

Compact UNH divider design

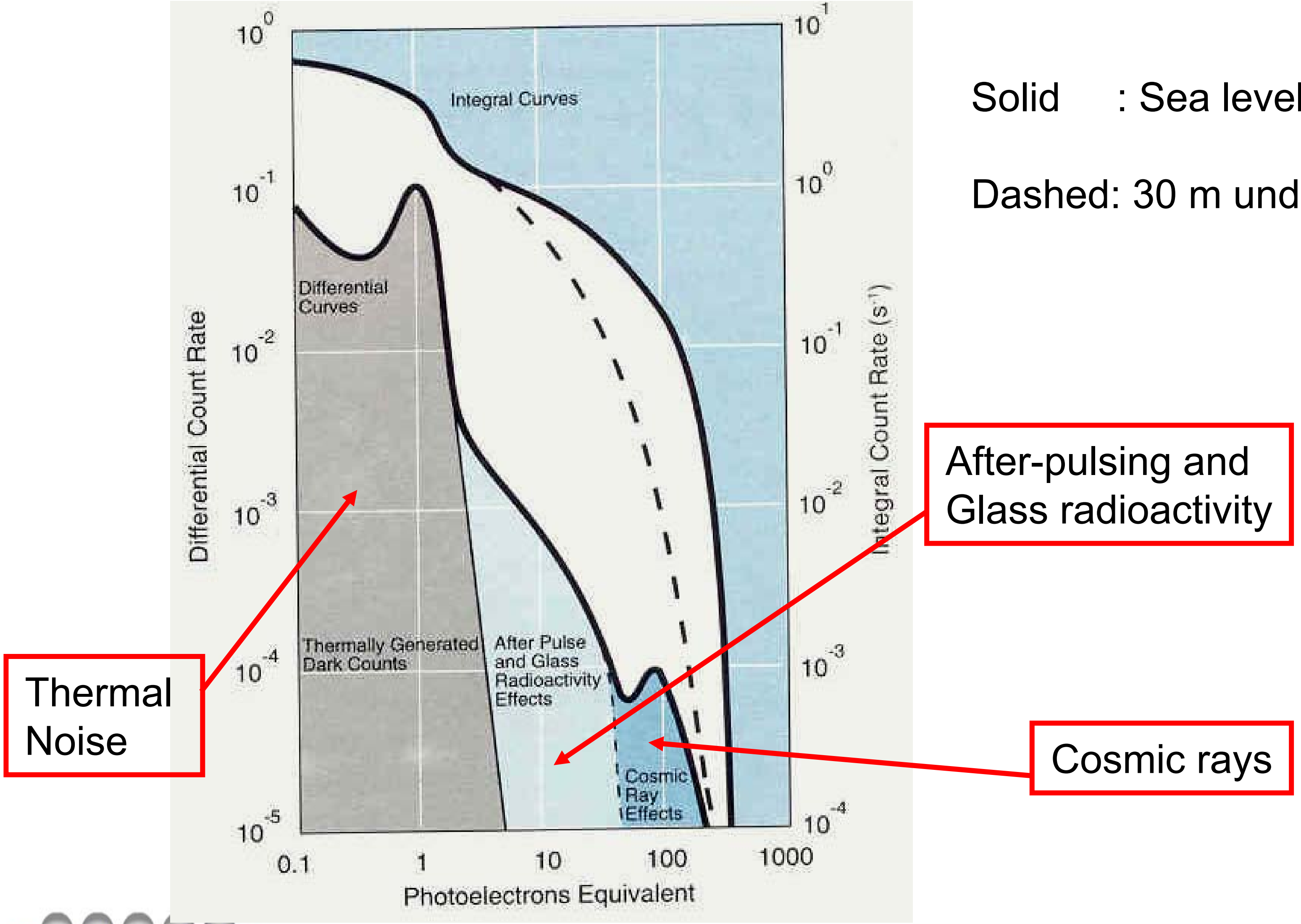


Electrostatics near cathode at −HV



Stable performance with negative high voltage is achieved by
Eliminating potential gradients in the vicinity of the photocathode.
The electrostatic shielding and the can of the crystal are both
Maintained at cathode potential by this arrangement.

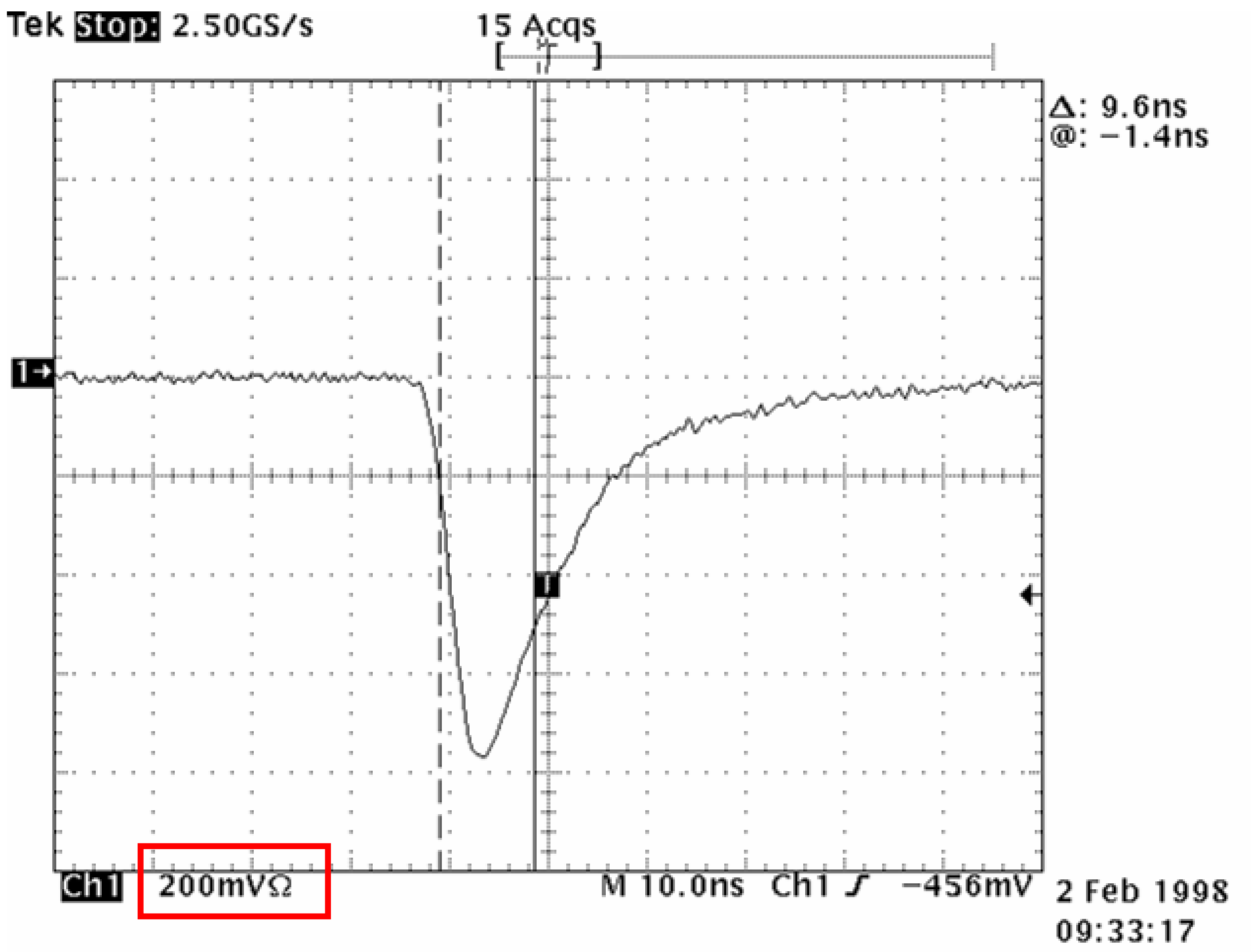
Dark counts



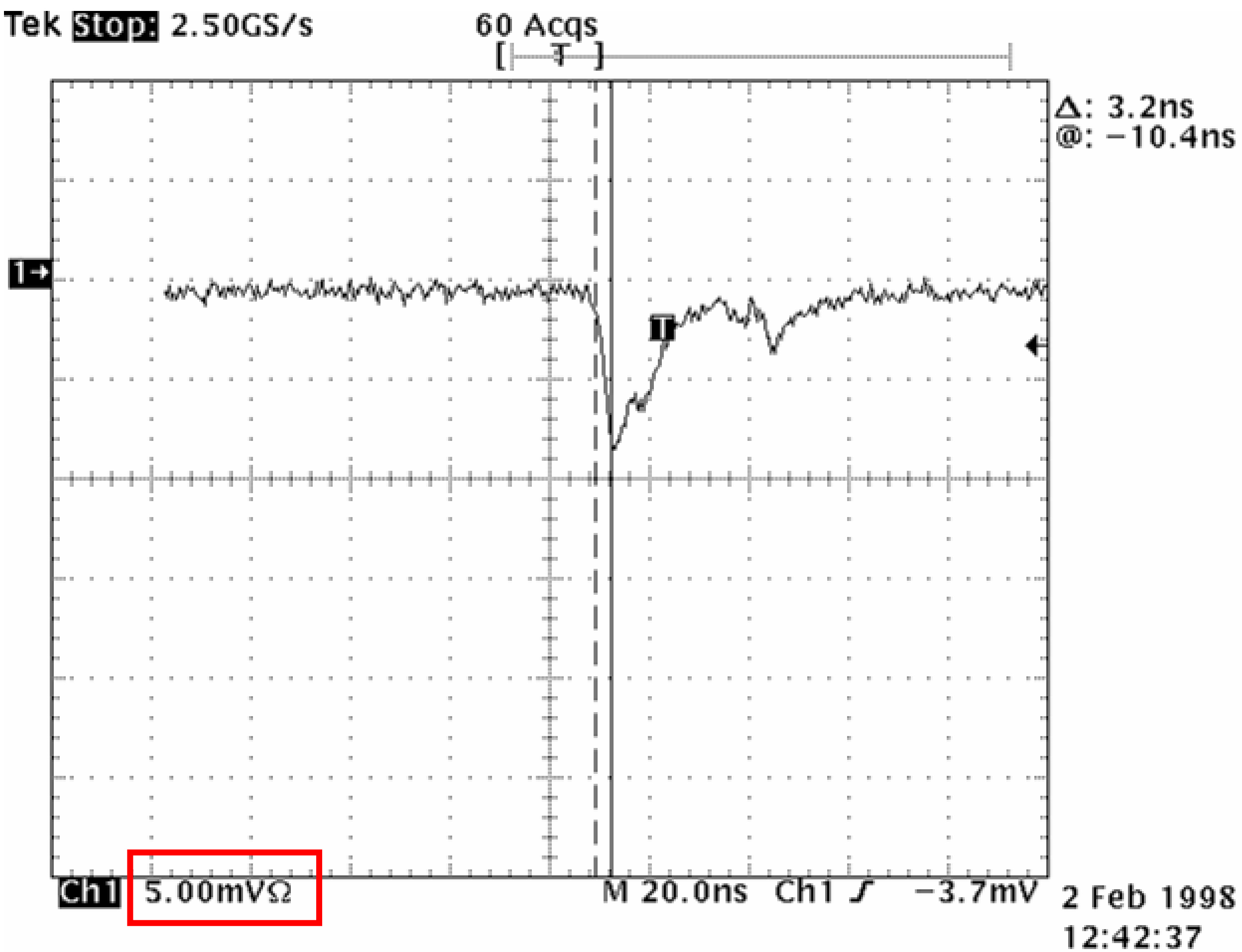
Solid : Sea level

Dashed: 30 m underground

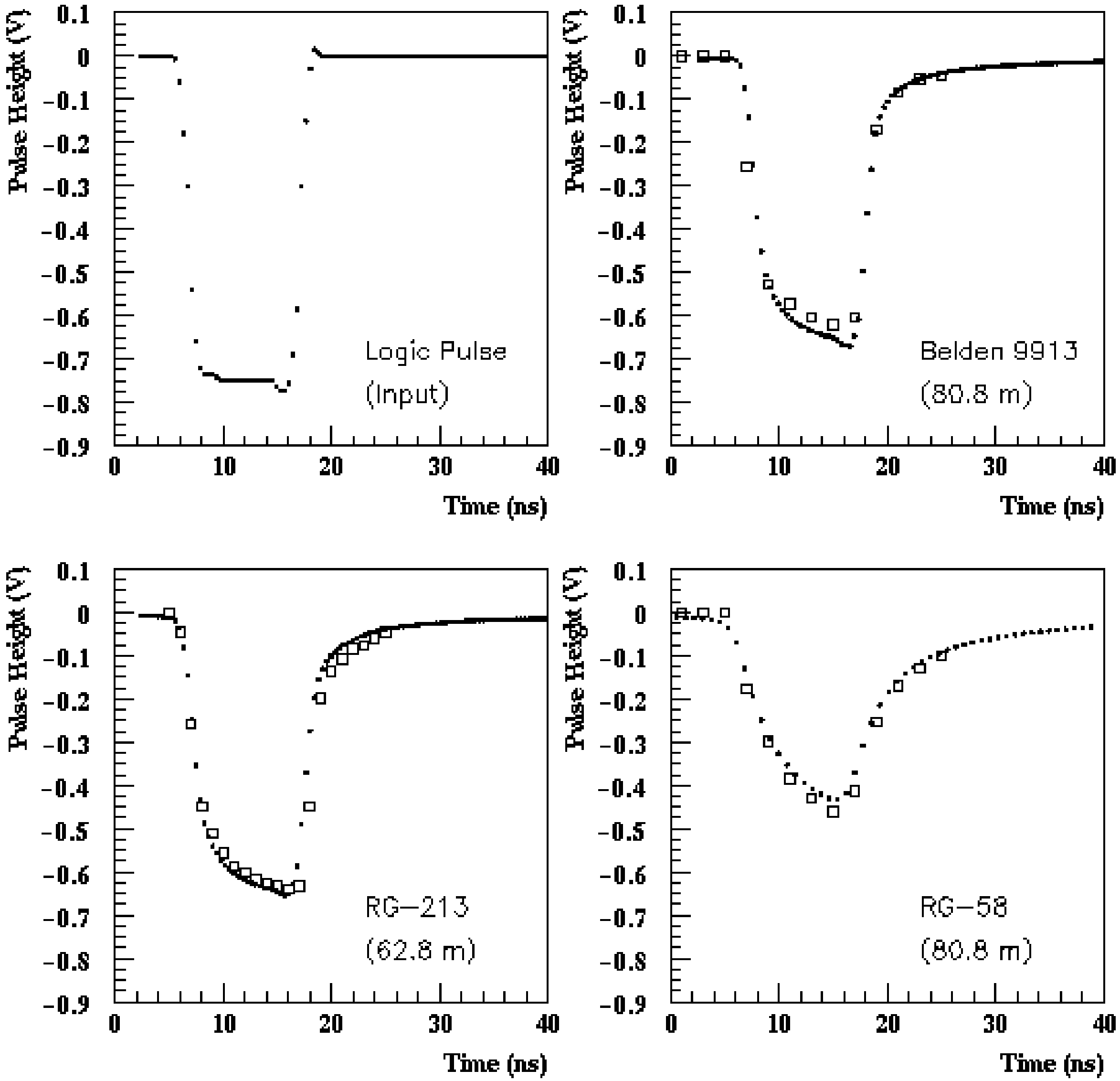
Signal for passing tracks



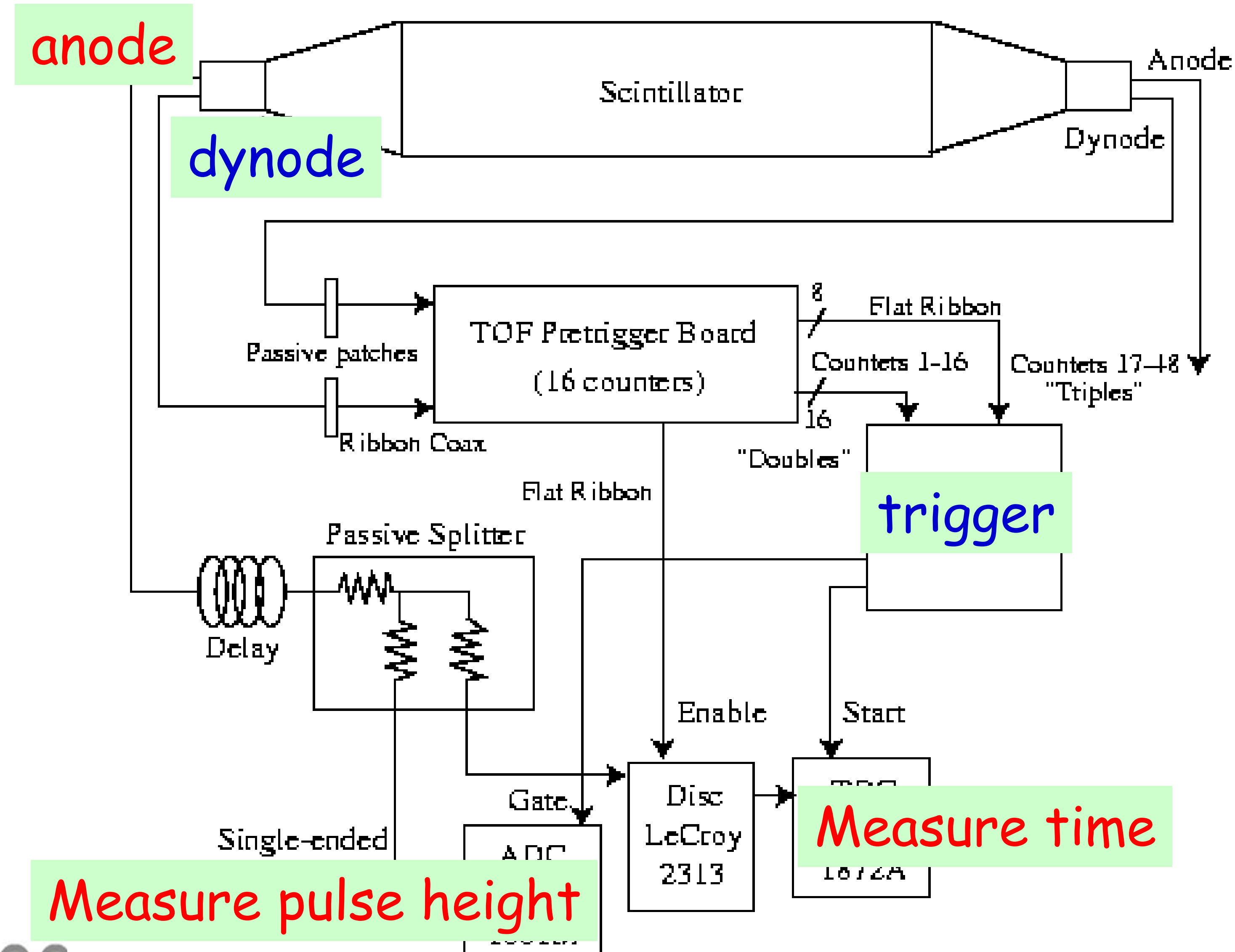
Single photoelectron signal



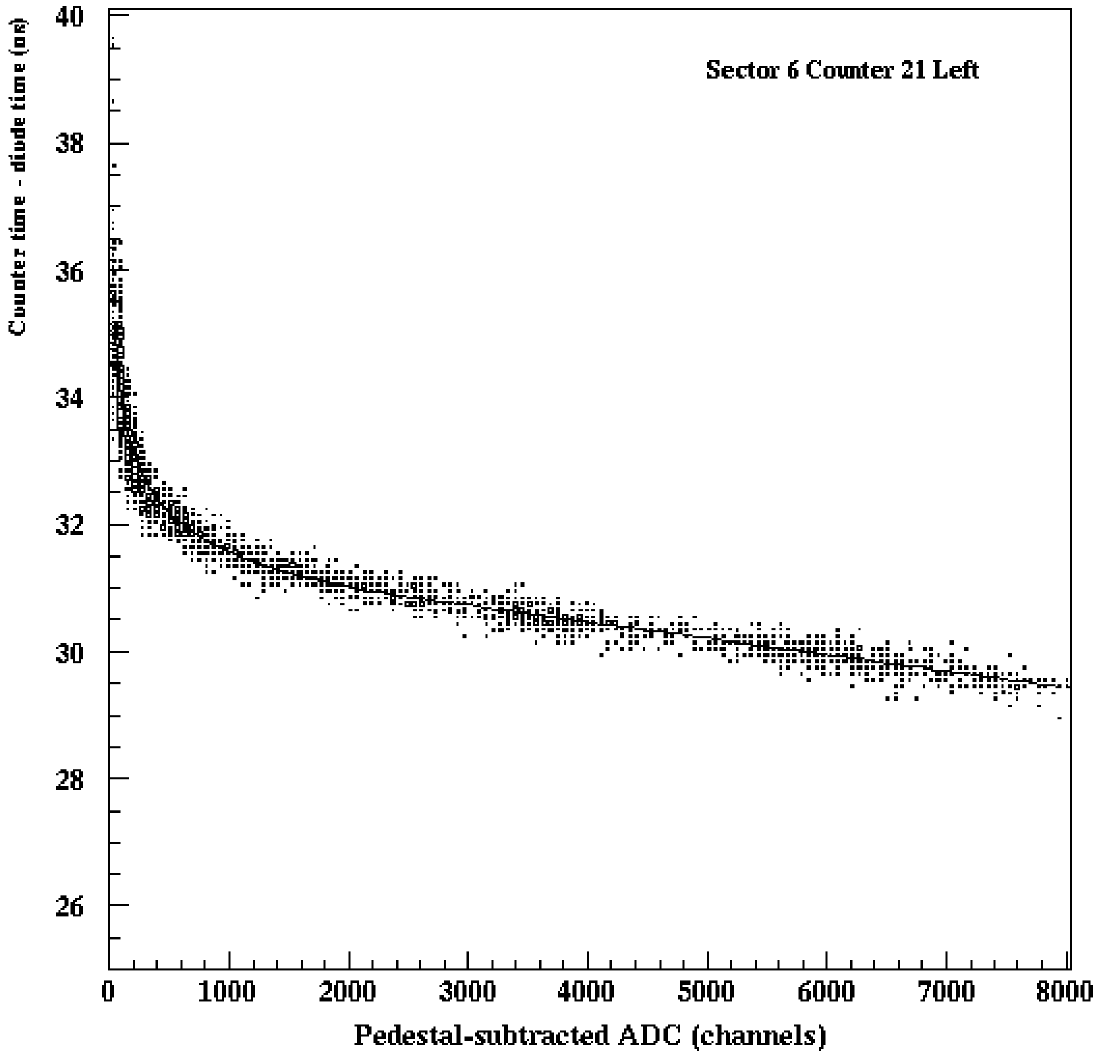
Pulse distortion in cable



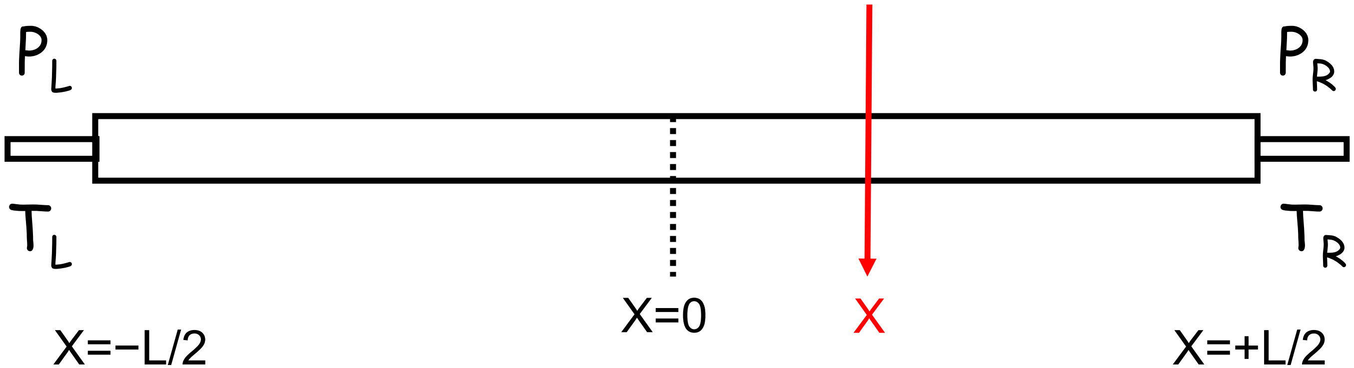
Electronics



Time-walk corrections



Formalism: Measure time and position



$$T_L = T_L^0 + x / v_{eff} \qquad T_R = T_R^0 - x / v_{eff}$$

$$T_{ave} = \frac{1}{2}(T_L + T_R) = \frac{1}{2}(T_L^0 + T_R^0)$$

Mean is independent of x!

$$x = \frac{v_{eff}}{2}\left[(T_L - T_R) - (T_L^0 - T_R^0)\right] \rightarrow \frac{v_{eff}}{2}(T_L - T_R)$$

From single-photoelectron timing to counter resolution

The uncertainty in determining the passage of a particle through a scintillator has a statistical component, depending on the number of photoelectrons N_{pe} that create the pulse.

$$\sigma_{TOF}(ns) = \sqrt{\sigma_0^2 + \frac{\sigma_1^2 + (\sigma_P \cdot L/2)^2}{N_{pe} \cdot \exp(-L/2\lambda)}} \qquad N_{pe} \approx 1000$$

$\sigma_0 = 0.062\ ns$ Intrinsic timing of electronic circuits

Single Photoelectron Response:

$\sigma_1 = 2.1\ ns$ Combined scintillator and pmt response

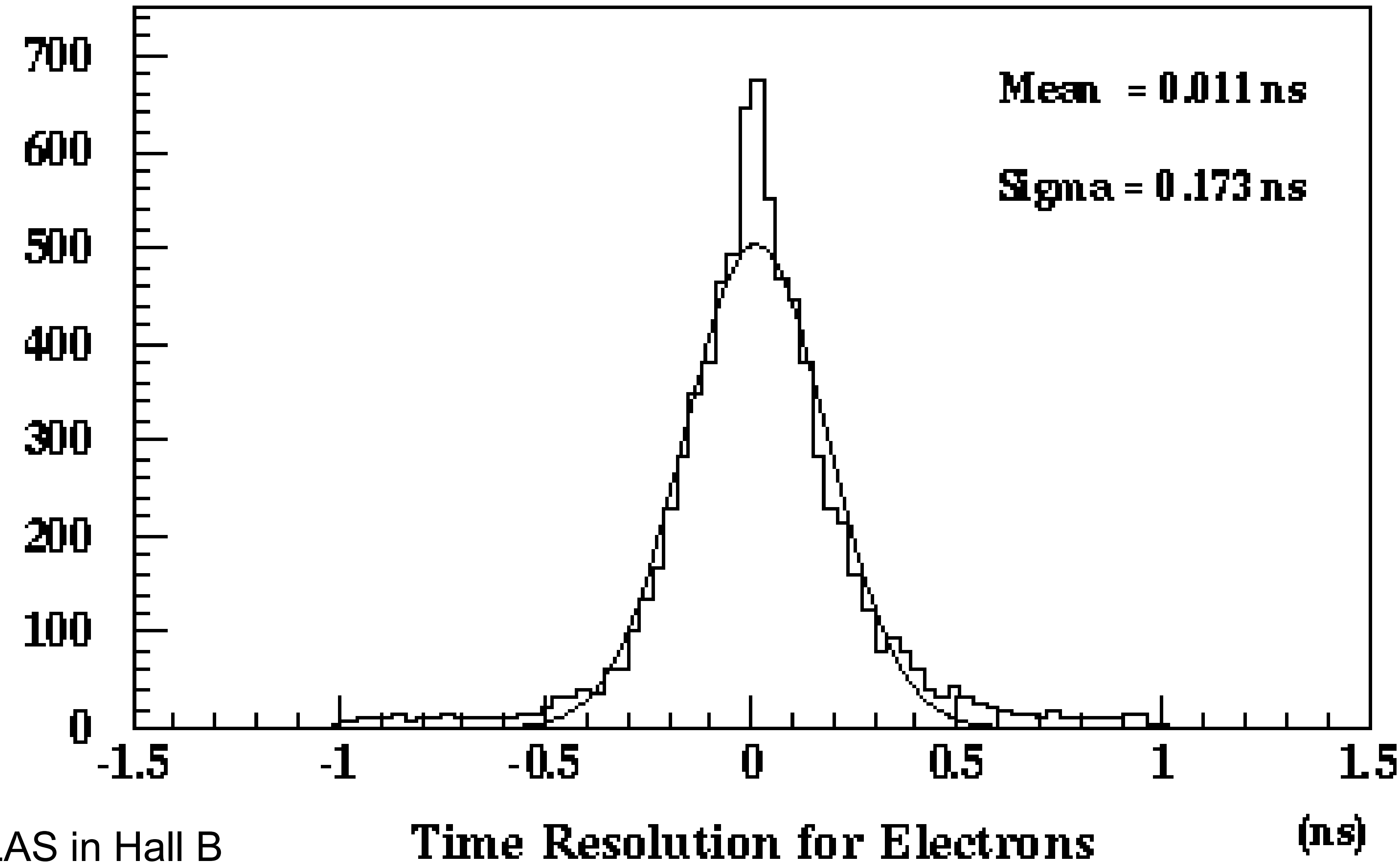
$\sigma_P = 0.0118\ ns/cm$ Average path length variations in scintillator

$$\lambda = 134cm + 0.36 \cdot L \quad (15cm\ counters)$$

$$\lambda = 430\,cm \quad (22\,cm\ counters)$$

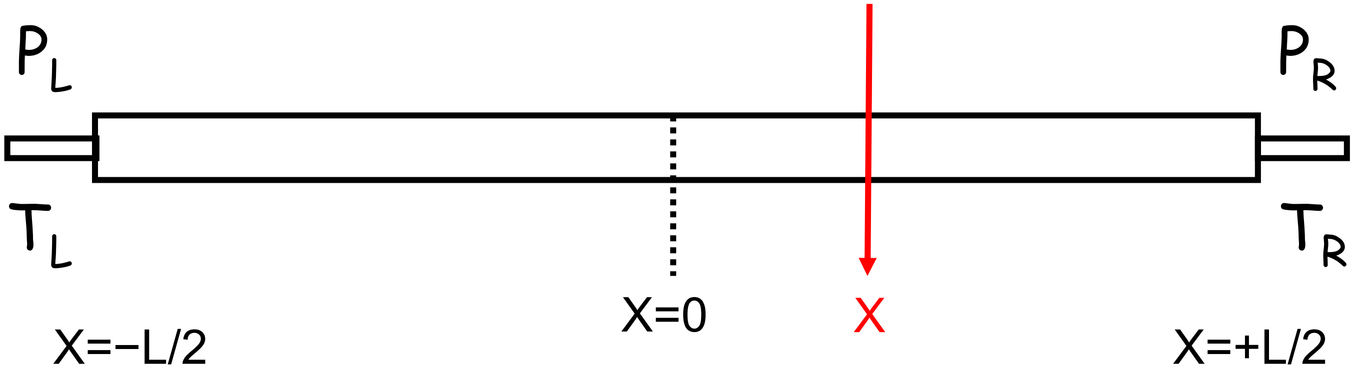
Note: Parameters for CLAS

Average time resolution



CLAS in Hall B

Formalism: Measure energy loss

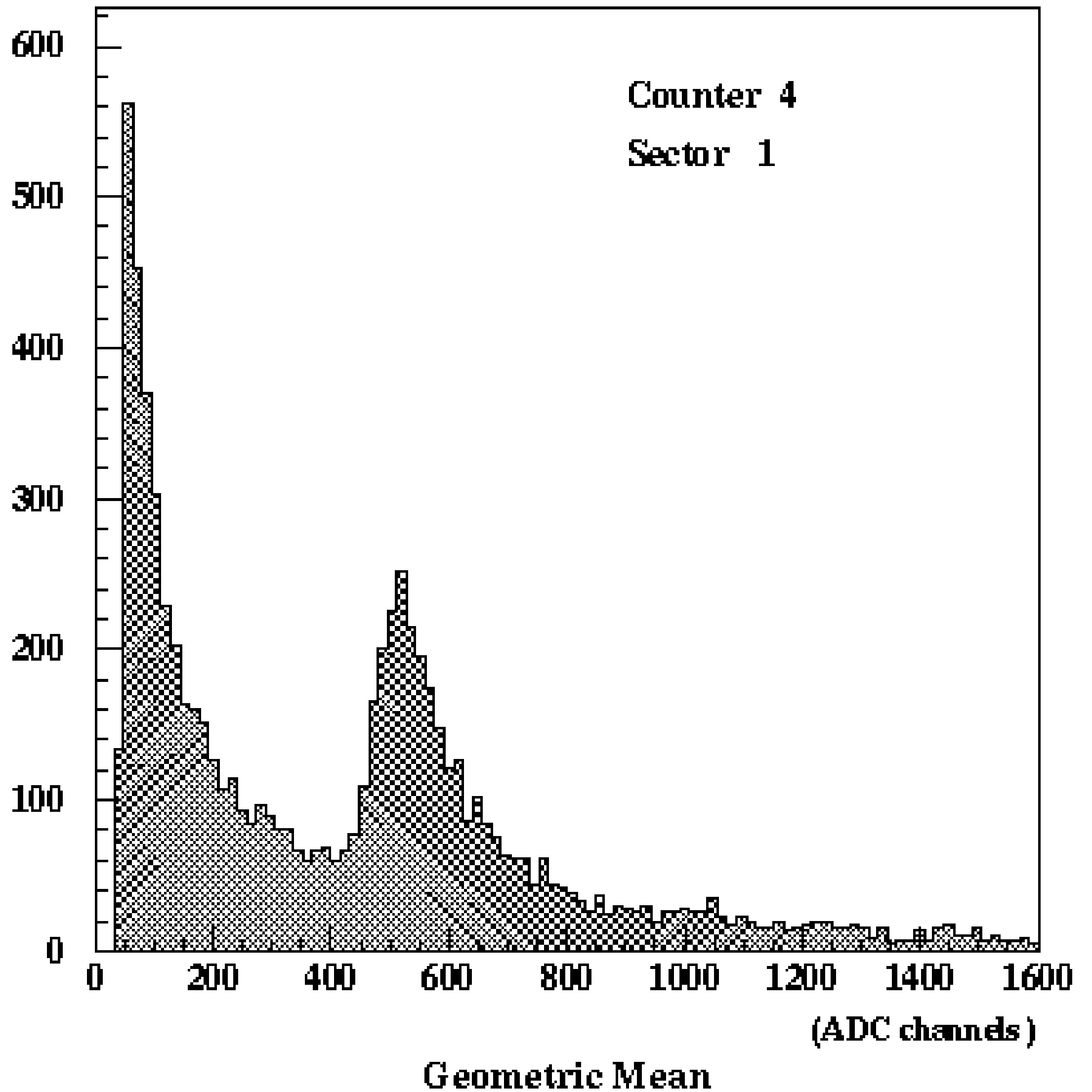


$$P_L = P_L^0 e^{-x/\lambda} \qquad P_R = P_R^0 e^{x/\lambda}$$

$$Energy = \sqrt{P_L \cdot P_R} = \sqrt{P_L^0 \cdot P_R^0}$$

Geometric mean is independent of x!

Energy deposited in scintillator



Uncertainties

Timing

Assume that one pmt measures a time with uncertainty δt

$$\delta t_{ave} = \frac{1}{2}\sqrt{\delta t_L^2 + \delta t_R^2} \sim \frac{\delta t}{\sqrt{2}}$$

$$\delta x = (v_{eff} \cdot \frac{1}{2})\sqrt{\delta t_L^2 + \delta t_R^2} \sim v_{eff} \cdot \frac{\delta t}{\sqrt{2}}$$

Mass Resolution

$$m = \frac{E}{\gamma} \qquad \rightarrow m^2 = (1-\beta^2)\,E^2 = \left(\frac{1-\beta^2}{\beta^2}\right)p^2$$

$$\left(\frac{\delta m}{m}\right)^2 = \gamma^4\left(\frac{\delta\beta}{\beta}\right)^2 + \left(\frac{\delta p}{p}\right)^2$$

Integral magnetic shield

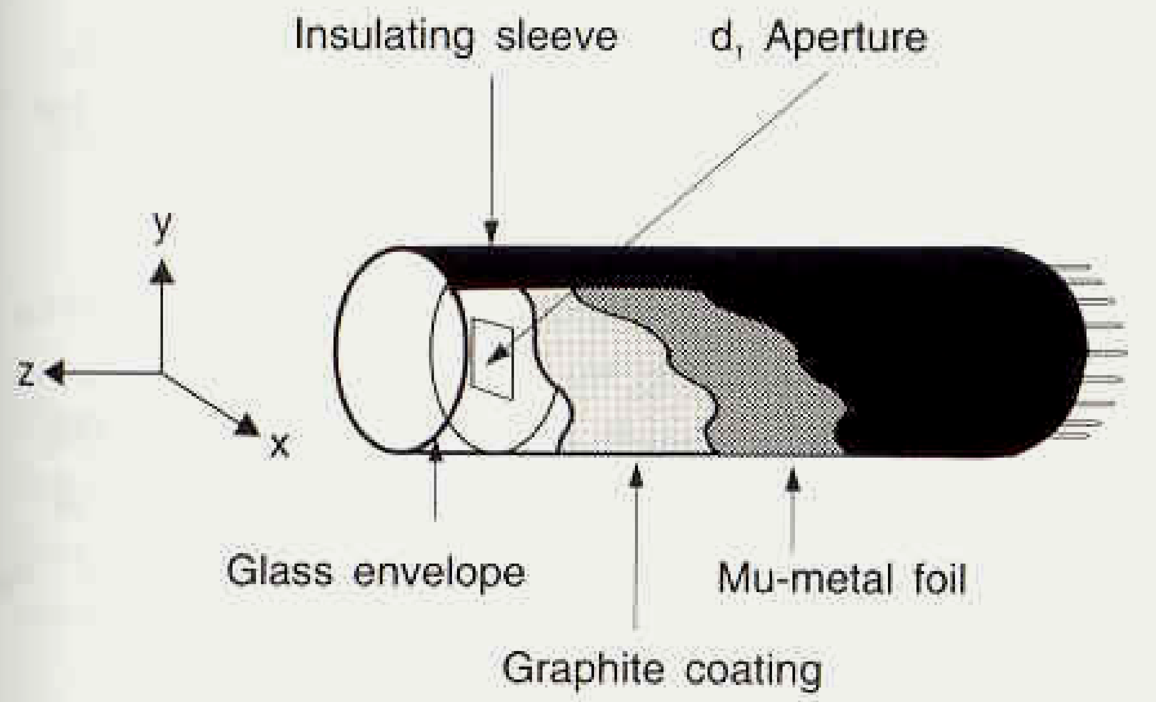


Figure 31

Cut away section illustrating the construction of the integral mu-metal shield. The co-ordinate axes adopted for the photomultiplier are also shown.

Example: Kaon mass resolution by TOF

$$P_K = 1 \ GeV/c \qquad E_K = \sqrt{0.495^2 + 1} = 1.116 \ GeV$$

$$\beta_K = \left(\frac{P_K}{E_K}\right) = 0.896 \qquad \gamma_K = \left(\frac{E_K}{m_K}\right) = 2.26$$

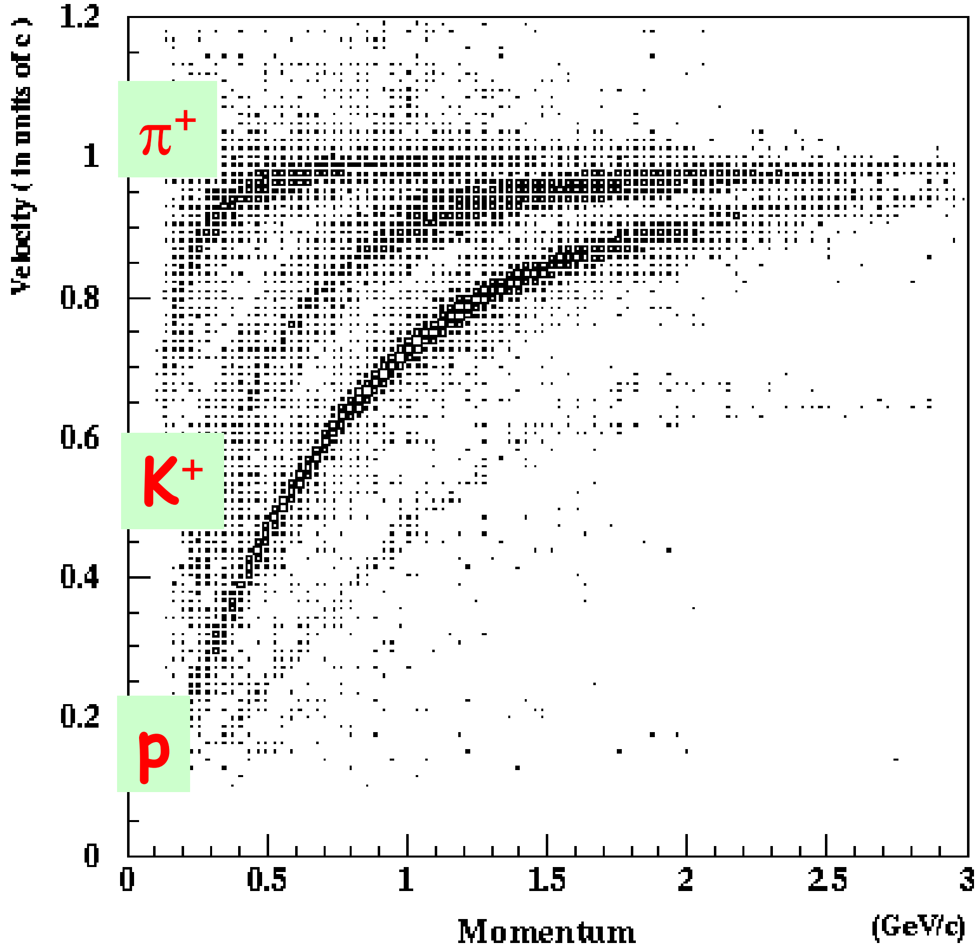
For a flight path of d = 500 cm, $t = \left(\frac{500 \ cm}{0.896 \cdot 30 \ cm/ns}\right) = 18.6\, ns$

Assume $\delta t = 0.15\, ns$ $\left(\frac{\delta p}{p}\right) = 0.01$

$$\left(\frac{\delta m}{m}\right)^2 = 2.26^4\left(\frac{0.15}{18.6}\right)^2 + (0.01)^2 = 0.042^2 \qquad \to \delta m_K \sim 21\, MeV$$

Note: $\left(\frac{\delta m}{m}\right) \xrightarrow[\gamma^2 \to \infty]{} \infty \left(for \ fixed \ \frac{\delta \beta}{\beta} \right)$

Velocity vs. momentum



Summary

- Scintillator counters have a few simple components
  - Systems are built out of these counters
  - Fast response allows for accurate timing
- The time resolution required for particle identification is the result of the time response of individual components scaled by $\sqrt{N_{pe}}$

Magnetic fields

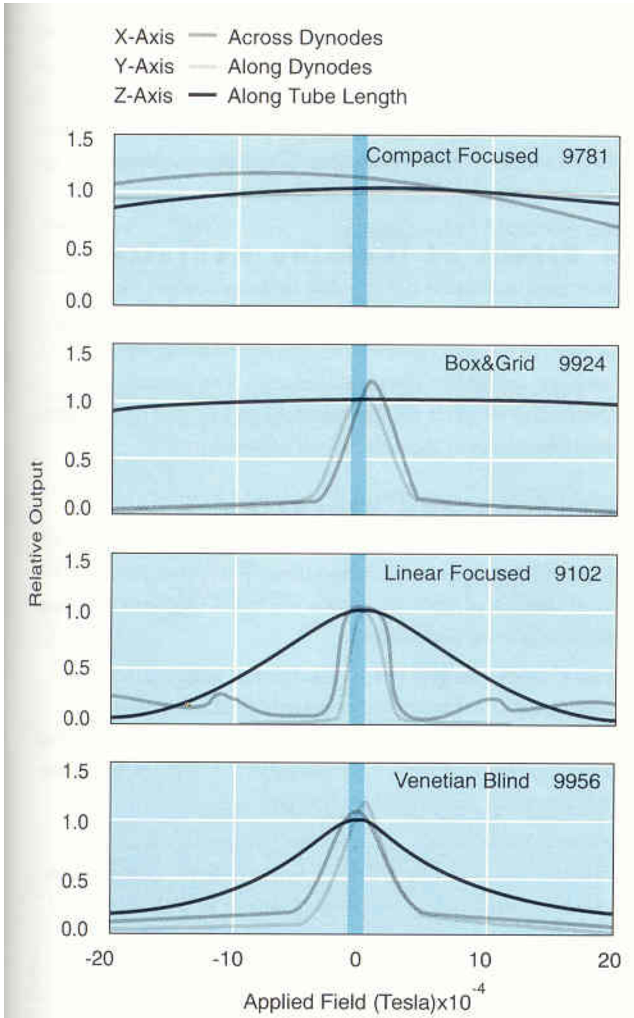


Figure 30
Relative output as a function of external magnetic field. (For photomultipliers operated at normal gain).